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Potash Availability— Market Economy Countries

A Minerals Availability Appraisal

By D. E. Sullivan and N. Michael

UNITED STATES DEPARTMENT OF THE INTERIOR

(United States. Bureau of Mines)

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PREFACE

The Bureau of Mines is assessing the worldwide availability of selected minerals of economic significance, most of which are also critical minerals. The Bureau identifies, collects, compiles, and evaluates information on producing, developing, and explored deposits, and on mineral processing plants worldwide. Objectives are to classify both domestic and foreign resources, to identify by cost evaluation those demonstrated resources that are reserves, and to prepare analyses of mineral availability.

This report is one of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources. Questions about, or comments on, these reports should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., NW., Washington, DC 20241.

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UNIT OF MEASURE ABREVIATIONS USED IN THIS REPORT

h	hour	pct	percent
kg/L	kilogram per liter	psi	pound per square inch
km	kilometer	mt	metric ton
km^2	square kilometer	mt/yr	metric ton per year
m	meter	yr	year

POTASH AVAILABILITY—MARKET ECONOMY COUNTRIES

A Minerals Availability Appraisal

By D. E. Sullivan[1] and N. Michael[2]

ABSTRACT

The Bureau of Mines investigated the availability of potash from 68 mines and deposits in 12 market economy countries (MEC's) containing, at the demonstrated resource level, approximately 11.7 billion metric tons (mt) of potash in assay terms of contained K_2O; K_2O as used by industry as a standard of comparison for the different forms of potash. These resources include almost 190 million mt in the United States, 9.63 billion mt in Canada, approximately 430 million mt in Western Europe (France, Federal Republic of Germany, Italy, Spain, and the United Kingdom), 1.24 billion mt in the Middle East (Israel and Jordan) and over 220 million mt in other countries (Brazil, Chile, and the Congo).

This analysis has determined that future production of potash in MEC's will most likely continue to be from the large resources associated with producing operations in Canada. Based solely on the demonstrated resources included in this study, potash mining in the United States would decline while overseas production from MEC's can continue into the next century at near current production levels. However, timely development of new or inferred resources would offset any such decline.

Producing mines in Canada have the resources to increase and maintain increased production well into the next century. For U.S. potash users, Canada is a long-term stable and secure source.

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INTRODUCTION

The purpose of this study is to evaluate resources of potash in market economy countries (MEC's) and to assess the related cost of production to recover these resources. Potash is not considered a strategic and critical mineral, but it is essential in the production of food and agricultural products, a vital concern of the United States. This study presents an evaluation of significant potash deposits on a geographic basis, including the costs to transport products of these deposits to markets.

Potassium, along with phosphorus and nitrogen, is an essential nutrient for plant growth and is used extensively in fertilizers (*1*).[3] The principal source of potassium is mined potash. Potash is the term used for a variety of naturally occurring potassium-bearing minerals and mineral products containing potassium. Sylvite, which is potassium chloride (KCl) is the most important potassium mineral. The product form of potassium chloride is referred to as muriate of potash. Sylvinite, a mixture of sylvite and halite (NaCl), is commercially the most important naturally occurring potassium ore because of its relatively high potassium content and ease of beneficiation. Additional potassium minerals that are mined include langbeinite in the United States, and kainite in Italy. Other naturally occurring potassium minerals include carnallite and polyhalite. Important naturally occurring potassium minerals and their chemical compositions are shown in table 1.

Table 1.—Naturally occurring potassium minerals considered in this analysis (*1-2*)

Mineral	Chemical composition	Location of mining[1]
Sylvite	KCl	United States, Canada, Federal Republic of Germany, France, Spain, United Kingdom.
Carnallite	$KCl \cdot MgCl_2 \cdot 6H_2O$	None.
Kainite	$KCl \cdot MgSO_4 \cdot 3H_2O$	Italy.
Polyhalite	$K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	None.
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$	United States.
Brines	Various	United States, Israel, Jordan.

[1]Market economy countries.

The term K_2O is used by industry as a standard of comparison for the different forms of potash. The grade of potash products is measured in terms of the percent K_2O contained, although the products are not in the form of K_2O; K_2O best represents the potassium value that is used by plants as a fertilizer. Potash products are also differentiated into types based on grain size. The common sizes are granular, coarse, standard, and special standard. The value follows this size differentiation with granular sized potash generally having the highest worth.

Table 2 identifies the potash products that were assumed to be marketable at operations analyzed in this study. The most important potash products include potassium chloride, potassium sulfate, and potassium-magnesium sulfate. Potassium chloride accounts for 90 pct of the annual capacity in terms of K_2O equivalents of producing operations included in this study, potassium sulfate capacity accounts for 5 pct, and other potash products account for the remaining 5 pct. Most operations included in this study produced only one of these products; the operations in the Federal Republic of Germany (FRG) produced the largest variety of potash products. Canada, the second largest producer of potash in the world after the U.S.S.R., produces only muriate and exports over 90 pct of its potash production.

Table 2.—Marketable products containing potassium included in this analysis (*1*)

Potash product	Chemical composition	Grade, pct K_2O	Annual K_2O capacity, pct
Muriate	KCl	60-62	90
Sulfate	K_2SO_4	50-54	5
Potassium magnesium sulfate.	$K_2Mg_2(SO_4)_3$	22	
Manure salts	KCl	19	
Korn kali	(1)	40	
Patent kali	(2)	32	5
Kali magnesia	(1)	28	
Thomas kali	(1)	18-20	
Raw salts	(1)	19	
Magnesia kainite	(1)	12	

[1]Contains KCl and sometimes other materials including magnesium and phosphorus.
[2]Contains K_2SO_4 and magnesium.

In 1983, the United States imported one-sixth of world potash production, in terms of K_2O; more potash than any other country in the world. The United States consumed more than 20 pct of world production during 1983. About 93 pct of potash consumption in the United States is for agricultural fertilizer, 95 pct of which is in the form of potassium muriate (*3*). Potassium sulfate or other potassium fertilizers are used in situations where the chloride in muriate is not wanted such as the tobacco, grape, and citrus industries.

The United States imported three-fourths of its apparent consumption in 1982 and exported nearly one-third of its own production. During 1982, 90 pct of potash imported by the United States was from Saskatchewan, Canada. Among the reasons potash is both imported and exported are transportation costs and product types. Producers in the United States have a transportation advantage when shipping to countries of Central and South America. The United States exports much more potassium sulfate than it imports.

Domestic deposits were evaluated by personnel of the Bureau's Field Operation Centers and foreign data collection and cost estimation were performed under contract by Jacobs Engineering Group, Inc., Lakeland, FL; personnel of the Bureau's Minerals Availability Field Office, Denver, CO, evaluated the data and performed the economic evaluation analyses.

WORLD POTASH INDUSTRY

PRODUCTION

Potash was produced in 13 countries during 1983 (see table 3 and figure 1). The largest output was 9.3 million mt K_2O equivalent produced in the U.S.S.R. This was almost 35 pct of world production in 1983, an increase from 27 pct of world production in 1972 and 15 pct in 1962. Canada produced about 6.2 million mt K_2O equivalent in 1983, which was over 23 pct of world production, down from its 27 pct in 1980, but an increase from its share of 17 pct

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

Table 3.—World production of marketable potash (*4, 8*), thousand metric tons of K_2O equivalent

Region and country	1962	1972	1980	1982[p]	1983[e]
Market economy countries:					
North America:					
Canada (sales)	136	3,495	7,532	5,309	6,203
United States	2,225	2,412	2,239	1,784	[1]1,429
Total, North America	2,361	5,907	9,771	7,093	7,632
South America: Chile	18	24	25	22	22
Western Europe:					
France	1,722	1,760	1,894	1,701	1,900
Germany, Federal Republic of	1,940	2,845	2,737	2,057	2,100
Italy	154	216	156	146	140
Spain	235	638	658	692	[1]657
United Kingdom	0	0	321	401	[1]302
Total, Western Europe	4,051	5,459	5,766	4,997	5,099
Middle East:					
Israel	91	561	797	1,004	1,000
Jordan	0	0	0	9	170
Total, Middle East	91	561	797	1,013	1,170
Africa: Congo	0	287	0	0	0
Total market economy countries	6,521	12,238	16,357	13,125	13,923
Centrally planned economy countries:					
China	0	281	12	26	25
German Democratic Republic	1,752	2,458	3,422	3,434	3,430
U.S.S.R.	1,497	5,433	8,064	8,079	9,300
Total, centrally planned economy countries	3,249	8,172	11,498	11,539	12,755
Grand total	9,770	20,410	27,857	24,664	26,678

[e]Estimated. [p]Preliminary [1]Reported.

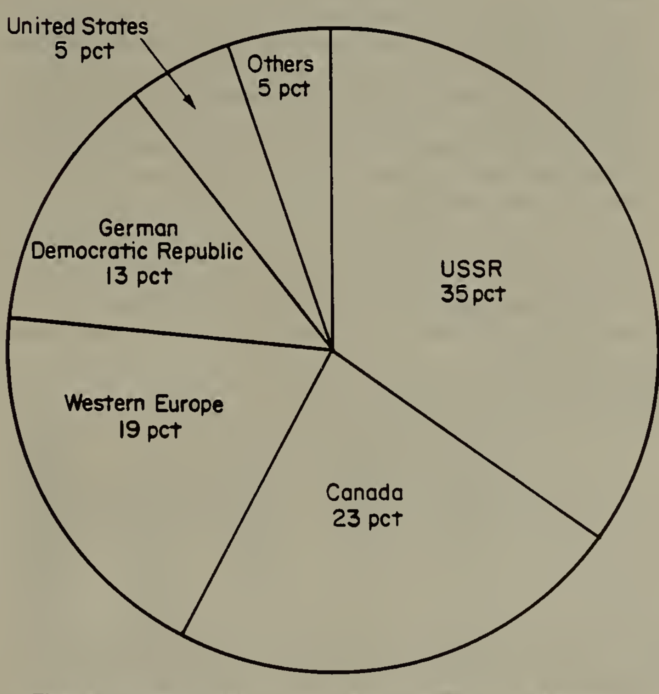

Figure 1.—1983 world production of potash, 26.678 million mt K_2O equivalents.

in 1972 and a large increase from the 1 pct in 1962. The Democratic Republic of Germany (GDR), which with the U.S.S.R. produced over 99 pct of the potash produced in centrally planned economy countries, produced 3.4 million mt K_2O equivalent in 1983, which was almost 13 pct of world production, about the same share that they produced in 1972, but down from 18 pct produced during 1962. The Federal Republic of Germany (FRG) produced 2.1 million mt K_2O equivalent, which was almost 8 pct of world production during 1983, down from the 14 pct of world production they produced during 1972 and 20 pct during 1962. The United States produced over 1.4 million mt K_2O equivalent during 1983 which was over 5 pct of world production. The U.S. production was 8 pct of world production in 1980, 12 pct during 1972, and 23 pct during 1962. France produced 1.9 million mt during 1983 which was over 7 pct of world production; this was down from 9 pct of world production during 1972 and 18 pct during 1962. The production in centrally planned economy countries, particular the U.S.S.R., has grown much faster than the production in market economy countries. Market economy countries produced 67 pct of world output during 1962; declining to 60 pct during 1972 and 52 pct during 1983.

The 10 mines that produced potassium muriate in Canada during 1983 were all located in Saskatchewan Province. They were operated by six companies, Cominco Ltd., International Minerals & Chemical Corp. (Canada) Ltd. (IMCC), Noranda Mines Ltd., PPG Industries Canada Ltd., Potash Co. of America (PCA), and Potash Corp. of Saskatchewan (PCS). Two mines are being developed in New Brunswick, one by Denison Potcan Potash Co. and the other by PCA. Numerous other prospects in Saskatchewan and one in Manitoba have been explored.

Products of potash operations or proposed operations in the United States are shown in table 4. Eleven of these mining operations produced potash in the United States during 1982 (*4*). These operations produced muriate of potash from sylvinite ore, potassium-magnesium sulfate from langbeinite ore, and sulfate of potash from a combination of

Table 4.—Potential products of potash mines and deposits in the United States in 1982

Property name, by State	Muriate	Potassium-magnesium sulfate	Sulfate	Other[1]
California:[2]				
Salton Sea[3]	X	X		X
Searles Lake	X		X	X
New Mexico:				
AMAX Chemical	X			
Hecla-Day Potash Lease[3]	X	X	X	
Hobbs Potash, Kerr-McGee	X			
Hodges Potash Property[3]	X	X		
IMC	X	X	X	
Mississippi Chemical Mine	X			
Nash Draw, Duval		X		
National Potash Co.	X			
Noranda Prospect[3]	X			
Potash Co. of America	X		X	
Utah:				
Bonneville (Wendover)	X			X
Cane Creek, Texasgulf, Inc.	X			
Little Mountain, GSL			X	X

[1]Includes manure salt, table salt, sodium sulfate, and magnesium chloride.
[2]These deposits produce or would produce potash as a minor byproduct and are not included in the availability analysis.
[3]Proposed mine.

sylvinite and langbeinite ores at IMC, kainite at GSL, and complex brines at Searles Lake. Seven of these are underground producing operations located in New Mexico. They are the AMAX Chemical mine, Hobbs Potash facility formerly owned by Kerr-McKee and now owned by Vertac, the IMC mine, the Nash Draw Mine owned by Duval Corp., the PCA mine, the Mississippi Chemical Mine, and the National Potash Co. mine. The Mississippi Chemical Mine has been shut down since January 1983 because of low worldwide demand and prices for potash. The National Potash Co. mine has been shut down since February 1982.

Three companies produced potash in Utah during 1982. Kaiser Chemicals of Kaiser Aluminum and Chemical Corp., produced muriate of potash from natural near surface brines at the west end of the Bonneville Salt Flats near Wendover; Texasgulf, Inc., using solution mining methods produced muriate of potash from its Cane Creek operation near Moab, that once was a conventional underground mine; and the Little Mountain Potash Operation of Great Salt Lake Minerals and Chemical Co. (GSL) produced sulfate of potash, sodium chloride, sodium sulfate, and magnesium chloride from the Great Salt Lake.

The only potash producing operation in California is the Kerr-McGee Chemical operation at Searles Lake. It produces muriate and sulfate of potash as byproducts of the soda ash (Na_2CO_3), borax ($Na_2B_4O_7$), and salt cake (Na_2SO_4) operations. The operations consist of three chemical plants, the Trona, the Argus, and the Westend plant. Potash is produced only at the Trona plant. California also has a brine deposit at the Salton Sea which could produce potash as a byproduct. Neither deposit in California was included in the availability analysis because the production of potash, although equivalent to some other U.S. mines, is a byproduct and is only a small part of the 'output.

When economic conditions are poor, producers take various measures to cut costs so they can continue to operate. Between 1982 and 1984, because of the poor economic climate for potash in the United States, several mines have taken extended vacations by temporarily closing for several months or have operated at less than full capacity for extended periods of time. The National Potash Co. mine and the Mississippi Chemical Mine have not been able to reduce costs sufficiently and have been forced to shut down for economic reasons.

Eight operations included in this study produced muriate of potash and various other potassium and other minerals from mines located in the Federal Republic of German (FRG). They were all owned and operated by one company, Kali und Salz AG (K&S). Table 5 shows the variety of potassium products that are produced by these mines.

Table 5.—Potassium products from producing mines in the Federal Republic of Germany (*2*)

Product	K_2O, wt pct	Producing mines[1]
Muriate	60-62	1-8.
	50	2-3, 6.
	40	3, 6.
Sulfate	50-54	2, 8.
Korn Kali	40	1, 3, 6.
Patent Kali	32	8.
Kali magnesia	28	6.
Thomas Kali	18-20	1.
Raw salts	19	7.
Magnesia kainit	12	1, 6.

[1]Producing mines:
1—Bergmannssegen-Hugo
2—Hattorf
3—Neuhof-Eilers
4—Niedersachsen-Riedel
5—Salzdetfurth
6—Siegfried-Giesen
7—Sigmundshall
8—Wintershall

Four mines produced muriate of potash in Spain during 1982. Two mines were operated by Union Explosivos Rio Tinto S.A., one by Potasas de Navarra S.A., and one by Minas de Potasas de Suria S.A.

Three mines produced muriate of potash in France. They were all owned by Mines de Potasse d'Alsace.

Three mines produced sulfate of potash in Italy. Two were owned by Industria Sali Potassici e Affini (ISPEA) and one by Societa per L'Industria del Salgemma S.p.A. (EMSAMS). All Italian potash production is located in Sicily.

One operation in Jordan utilizes the brines of the Dead Sea to produce muriate of potash. It is owned by the Arab Potash Co.

The Dead Sea Works in Israel, majority owned by the Government of Israel, also exploits the brine of the Dead Sea to produce muriate of potash and other minerals.

One facility in the United Kingdom produces muriate of potash from an underground mine. It is owned and operated by Cleveland Potash Ltd.

Brazil has two potash deposits that are being developed by Petrobras Mineracão S.A. Corfo in Chile is considering the development of a brine operation. The Government-owned Holle Mine in the People's Republic of the Congo has produced potash in the past and still contains demonstrated resources of potassium ores. Development of potash has been considered in Thailand and Peru and several other countries.

EXPORTS, IMPORTS, AND CONSUMPTION

Aggregated world potash trade in terms of K_2O equivalents in 1983 is shown in table 6. This table shows

Table 6.—Aggregated world potash trade, 1983 (*9*), million metric tons (K_2O equivalent)

Destination, by continent	Exporting source, by continent				Total by continent[2]
	North America	Eastern Europe	Western Europe	Asia[1]	
North America	(3)	0.14	0.07	0.27	0.48
Eastern Europe	0.00	NAp	.03	.00	.03
Western Europe	.10	1.14	NAp	.34	1.58
Asia	1.63	.64	.49	NAp	2.75
Africa	.04	.03	.19	.08	.35
South America	.37	.77	.16	.01	1.31
Oceania	.21	.01	.00	.13	.35
Total, by continent exporting source[2]	2.36	2.73	.93	.82	6.84

NAp Not applicable.
[1]Includes Israel.
[2]Data may not add to totals shown because of independent rounding.
[3]This table does not show the volume of trade within continents, for example Canada shipped 4.14 million mt to the United States in 1983.

imports and exports by continent, with the United States and Canada shown together under North America. Not directly shown on the table are the exports from Canada to the United States, 4.14 million mt K_2O equivalents in 1983. This made Canada the largest exporter and the United States the largest importer of potash in the world in 1983. The table illustrates that, after Canada, Eastern Europe was the largest exporter, exporting 2.73 million mt. Western Europe exported 0.93 million mt and Asia (mostly Israel) exported 0.82 million mt. After the United States, Asia was the largest importer of potash, importing 2.75 million mt. Western Europe was second, importing 1.58 million mt and South America imported 1.31 million mt.

U.S. exports of muriate and sulfate in terms of product to country of destination for 1983 are shown in table 7. A total of nearly 386,000 mt of murite and 178,000 mt of sulfate were exported in that year. This table demonstrates that even though distribution of potash exports from the United States is widespread, 63 pct of the muriate went to four countries, New Zealand 24 pct, Japan 22 pct, Mexico 9 pct, and India 8 pct.

Table 8 shows U.S. imports for consumption of muriate of potash by country of origin for 1962, 1972, 1980, 1982, and 1983. Imports of muriate from Canada increased substantially between 1962 and 1980 with most of the increase occurring between 1962 and 1972. This is the period in which most Canadian potash mines were developed.

Almost 89 pct of the 1983 U.S. imports for consumption of muriate was from Canada. Figure 2 illustrates the growth in imports from Canada. Imports of muriate from Israel, the German Democratic Republic, and the U.S.S.R. also increased substantially between 1962 and 1982 with most of these increases occurring between 1972 and 1982. Imports from Israel and the German Democratic Republic also increased notably during 1983. Muriate imports from most other countries do not show specific trends.

Table 9 shows U.S. imports for consumption of potassium sulfate by country of origin for 1962, 1972, 1980, 1982 and 1983. Imports of sulfate from France and Italy were zero in 1983. Imports from the Federal Republic of Germany declined in 1982 but increased substantially in 1983. During 1983, the United States imported significantly more muriate of potash than it exported. During 1983 the United States exported much more sulfate than it imported.

Table 10 shows U.S. production, sales, exports, imports for consumption and apparent consumption of potash in all forms in terms of K_2O for 1962, 1972, 1980, 1982, and 1983. Production and sales were near the same level in 1980 and 1972 as 1962, but they were approximately 25 pct lower in 1982. In 1983, production was 20 pct below the 1982 level

Table 7.—U.S. exports of potash, by country, 1983 (*4*), metric tons

Country of destination	Muriate		Sulfate	
	Product[1]	[2]K_2O	Product[3]	[4]K_2O
Argentina	0	0	6,850	3,425
Australia	0	0	7,010	3,505
Bahamas	20	12	1,710	855
Belgium	7,600	4,560	0	0
Brazil	11,970	7,182	9,210	4,605
Canada	4,710	2,826	18,830	9,415
Chile	0	0	10,020	5,010
Colombia	6,720	4,032	6,060	3,030
Costa Rica	16,000	9,600	3,760	1,880
Denmark	23,790	14,274	0	0
Dominican Republic	19,850	11,910	1,520	760
Ecuador	5,440	3,264	0	0
Egypt	0	0	10,120	5,060
French West Indies	14,690	8,814	0	0
Guatemala	1,680	1,008	200	100
Haiti	0	0	110	55
Honduras	1,150	690	70	35
India	30,430	18,258	0	0
Italy	1,600	960	0	0
Jamaica	0	0	120	60
Japan	85,590	51,354	53,920	26,960
Korea, Republic of	180	108	110	55
Leeward and Windward Islands	1,100	660	350	175
Mexico	36,100	21,660	18,720	9,360
New Zealand	94,190	56,514	420	210
Nicaragua	0	0	5,900	2,950
Norway	6,200	3,720	0	0
Panama	2,820	1,692	1,470	735
Peru	5,430	3,258	4,750	2,375
Philippines	10	6	430	215
Saudi Arabia	90	54	100	50
Sweden	6,600	3,960	0	0
Switzerland	1,410	841	0	0
Taiwan	20	12	0	0
Thailand	0	0	6,000	3,000
Venezuela	60	36	9,150	4,575
Other	530	318	850	425
Total	385,980	231,588	177,760	88,880

[1]Minimum 60 pct K_2O.
[2]Estimated based on the K_2O grade of the muriate and sulfate.
[3]Includes potassium-magnesium sulfate.
[4]Potassium sulfate, 50 pct K_2O, potassium-magnesium sulfate is 22 pct K_2O.

Table 8.—U.S. imports for consumption of muriate of potash,[1] by country of origin (*4-8*), thousand metric tons

	1962		1972		1980		1982		1983	
	Product	K_2O	Product	K_2O	Product	K_2O	Product	K_2O	Product	K_2O
Canada	69	41	4,205	2,523	7,642	4,585	5,724	3,434	6,371	3,823
Chile	0	0	6	4	6	4	0	0	1	1
Congo	0	0	31	19	0	0	0	0	0	0
France	158	95	0	0	0	0	0	0	0	0
German Democratic Republic	0	0	0	0	57	34	86	52	136	82
Germany, Federal Republic of	137	82	(2)	(2)	10	6	3	2	30	18
Israel	0	0	160	96	312	187	353	212	510	306
Spain	43	26	0	0	11	7	50	30	53	32
U.S.S.R	8	5	0	0	38	23	74	44	76	46
Zaire	0	0	5	3	0	0	0	0	0	0
Other	0	0	1	1	3	2	0	0	(2)	(2)
Total[3]	414	248	4,408	2,645	8,079	4,848	6,290	3,774	7,177	4,306

[1]Minimum 60 pct K_2O. [2]Less than ½ unit. [3]Totals may not add because of independent rounding.

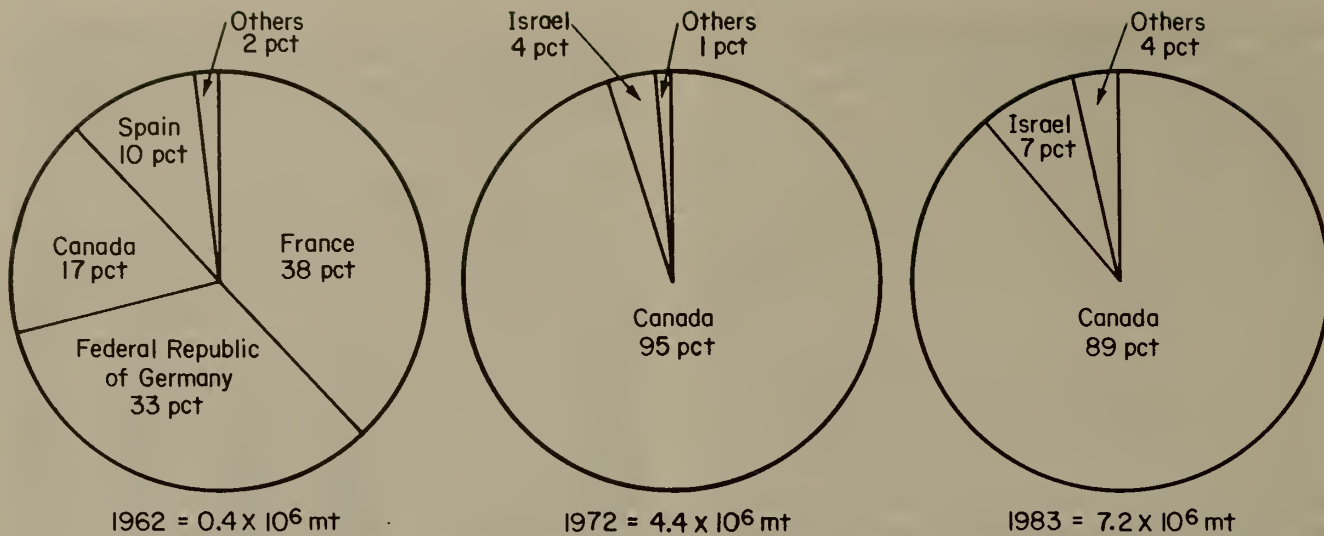

Figure 2.—U.S. imports for consumption of muriate of potash, by country of origin, for selected years.

Table 9.—U.S. imports for consumption of potassium sulfate,[1] by country (*4-8*), thousand metric tons

	1962		1972		1980		1982		1983	
	Product	^2K_2O	Product	^2K_2O	Product	^2K_2O	Product	^2K_2O	Product	^2K_2O
France	34	17	21	11	0	0	0	0	0	0
Germany, Federal Republic of	34	17	38	19	30	15	4	2	59	30
Italy	29	15	0	0	0	0	0	0	0	0
Spain	7	4	0	0	0	0	0	0	0	0
Other	0	0	(3)	(3)	14	7	8	4	(3)	(3)
Total[4]	104	52	60	30	44	22	12	6	59	30

[1]50 pct K_2O. [2]Estimated based on 50 pct K_2O in product. [3]Less than ½ unit. [4]Totals may not add because of independent rounding.

and sales were down 15 pct. Exports were over 80 pct greater in 1980 than 1982 but they declined in both 1982 and 1983. Imports have increased dramatically. In 1962 imports supplied just over 13 pct of apparent consumption in the United States, in 1972 imports grew to over 61 pct, in 1980, 1982, and 1983 they exceeded 75 pct of consumption. The growth of imports into the United States occurred during the period of development of the Canadian potash industry.

Table 10.—U.S. production, sales, exports, imports, and apparent consumption of potash (*4-8*), thousand metric tons K_2O equivalent

	1962	1972	1980	1982	1983
Production	2,225	2,412	2,239	1,784	1,429
Sales	2,469	2,375	2,217	1,784	1,513
Exports	461	693	840	519	300
Imports	310	2,686	4,972	3,858	4,440
Apparent consumption	2,319	4,368	6,349	5,123	5,653

EVALUATION METHODOLOGY

The data collected for this report were stored, retrieved, and analyzed in a computerized component of the Minerals Availability Program (MAP). The flow of the minerals availability evaluation process from deposit identification to analysis of availability information is illustrated in figure 3.

The analysis methodology of this study is as follows:

1. Deposits were selected to represent the significant producers of potash and include at least 85 pct of the production from market economy countries. Nonproducing properties are included if their tonnage and grade are comparable to producing operations.

2. The quantity and grade of potash resources were evaluated in relation to physical and technological conditions that affect production from each deposit as of the study date, January 1984.

3. Appropriate mining, concentrating, and processing methods were described for producing operations and proposed from nonproducing operations. Related capital investments and operating costs were then estimated, including a transportation cost to deliver the potash products to a port or a marketplace. For purposes of consistency, it was assumed in this report that all potash was transported to a local port for export unless that product was being used for internal domestic consumption. If internally consumed, a transportation cost to a typical consuming marketplace was included.

4. An economic analysis determined the average total production cost for each operation over its entire producing life, including a return on invested capital. This cost was then related to the total demonstrated tonnage of potash products that could potentially be recovered at a specified production level.

5. Upon completion of the individual property analyses, all properties included in the study were simultaneously analyzed and aggregated onto one or more cost tonnage curves. These curves are aggregations of the total potential potash product that could be produced over the life of each operation, ordered from the lowest cost deposits to the

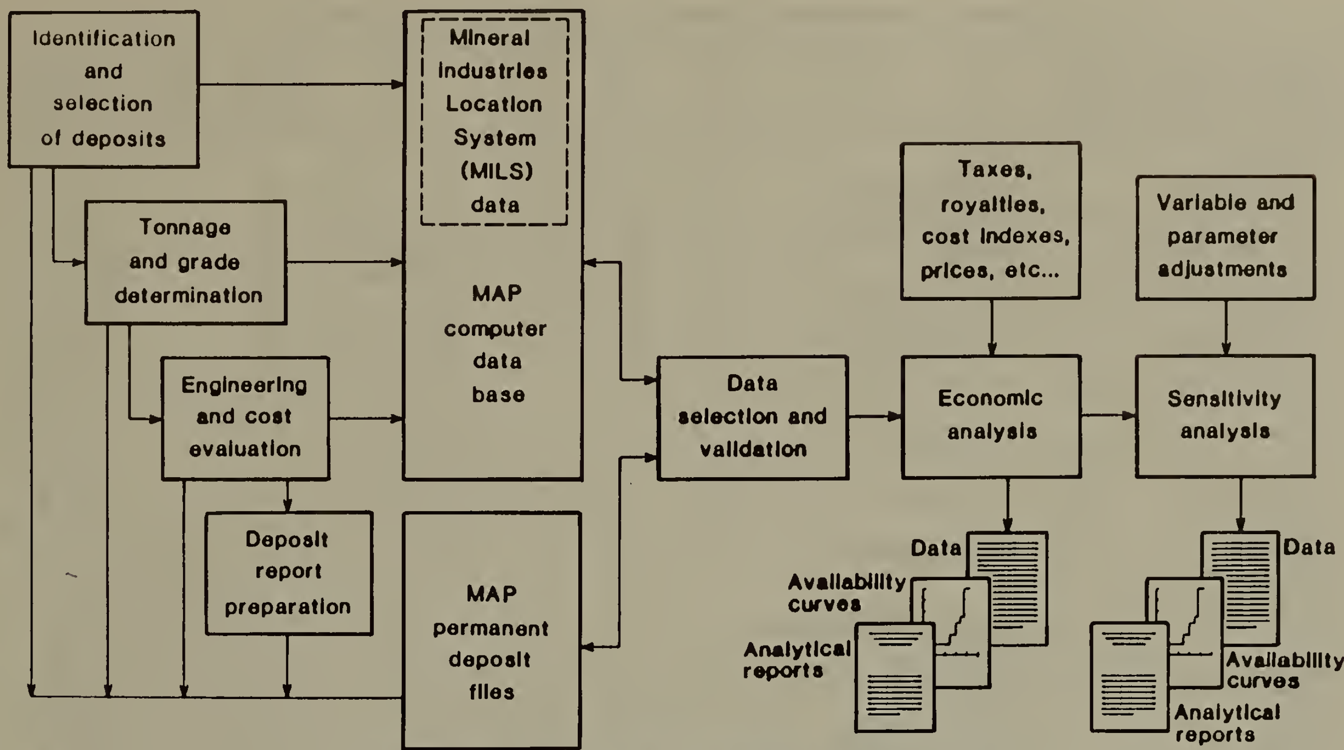

Figure 3.—Flow chart of mineral availability evaluation process.

highest. The curves illustrate the comparative costs associated with any given level of potential total output, and provide an estimate of what the average long-run potash price (in January 1984 dollars) would have to be in order for a given tonnage to be potentially available. The long-run price, which each operation would require to cover its average total cost of potash production, would provide revenues sufficient to cover the average total cost of production, including a return on investment high enough to attract new capital. The rate of return used in this study is a 15-pct discounted-cash-flow rate of return (DCFROR) on the total investments of each operation. In addition to the analysis showing total potential output, an analysis was performed relating cost to potential annual output.

Separate curves of cost-tonnage relationships were generated by geographic area and potash product. If a deposit produced more than one potash product it was included in more than one cost curve and an analysis was made of the percent of revenues derived from each potash product.

As stated in step 1, deposit selection was designed to include primary potash producing properties accounting for at least 85 pct of potash production from each significant producing market economy country, and developing, explored, and past producing properties where the demonstrated resource is equivalent to those of producing mines. As related to this study, reserves are potash mineralizations that can be mined, processed, and marketed at a profit under prevailing economic and technologic conditions. Resources are potash concentrations in such form that economic extraction of a commodity is currently or potentially feasible (*10*).

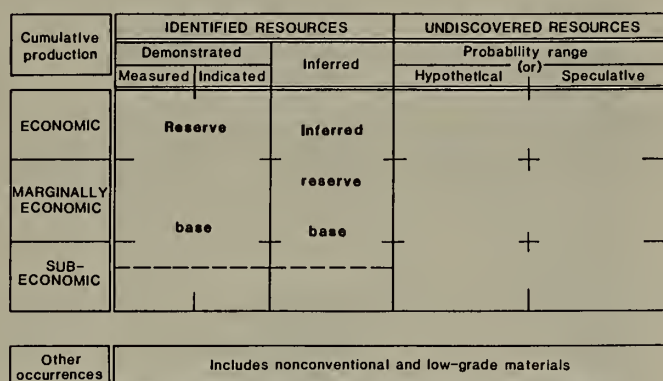

Figure 4.—Mineral resource classification categories.

For the deposits analyzed, tonnage estimates were made at the demonstrated resource level based on the mineral resource-reserve classification system (fig. 4) developed jointly by the Bureau of Mines and the U.S. Geological Survey (*10*). The demonstrated resource category includes measured plus indicated tonnages. Generally, reserve and resource tonnage and grade calculations presented in this paper were computed from specific measurements, samples, or production data, and from estimations made on geologic evidence.

RESOURCES

The 68 mines and deposits from 12 market economy countries that were included in the availability analysis are shown in table 11. Three additional deposits were considered but not included in the availability analysis. The

Table 11.—Potash mines and deposits included in the study, 1982

Country and deposit name	Owner	Status[1]	Mine method[2]	Mill method[3]	Potash product[4]	Initial year of production	Mill feed grade[5]	Mill capacity: Ore[6]	Mill capacity: Muriate product[7]
United States:									
New Mexico:									
AMAX Chemical	AMAX Chemical Corp	P	RP	FL	M	1952	A	B	B
Hecla-Day Potash Lease	Hecla-Day Mining Corp	N	RP	FL	M, S, KMg	NAp	A	B	A
Hobbs Potash Facility	New Mexico Potash Corp	P	RP	Cr	M	1965	A	A	B
Hodges Potash Property	Duval Corp	N	RP	FL, Cr	M, KMg	NAp	A	A	A
IMC	IMC	P	RP	FL	M, S, KMg	1940	A	B	A
Mississippi Chemical Mine	Mississippi Chemical Co.	S	RP	FL	M	1931	A	A	A
Nash Draw	Potash Producers, Inc.	P	RP	L	KMg	1964	A	A	A[8]
National Potash Co.	Mississippi Chemical Co.	S	RP	FL, Cr	M	1957	A	A	A
Noranda Prospect	Noranda Exploration Inc.	N	RP	FL	M	NAp	B	A	B
Potash Company of America	Ideal Basic Industries Inc.	P	RP	FL, Cr	M, S	1935	B	A	B
Utah:									
Bonneville (Wendover)	Kaiser Aluminum and Chemical Co.	P	BR	FL	M[9]	1937	A	C	A
Cane Creek	Texasgulf Inc.	P	SOL	FL	M	1964	D	A	A
Little Mountain	GSL Minerals	P	BR	Cr	S	1968	A	D	A[10]
Brazil:									
Fazendinha	Petrobrás Mineracão S.A.	N	RP	FL	M	NAp	B	A	A
Taquari-Vassouras	...do	N	RP	FL	M	NAp	B	A	A
Canada:									
Allan	Potash Corp. of Saskatchewan, Texasgulf.	P	RP	FL, Cr	M	1968	C	B	C
Borden	Unknown	N	RP	FL, Cr	M	NAp	C	B	C
Bredenbury	Potash Corp. of Saskatchewan	N	RP	FL, Cr	M	NAp	C	D	D
Burr	Unknown	N	RP	FL, Cr	M	NAp	C	B	C
Colonsay (CCP)	Noranda Mines Ltd.	P	RP	FL, Cr	M	1970	D	B	D
Cory Division	Potash Corp. of Sasketchewan	P	RP	FL, Cr	M	1969	C	A	B
Dundurn	Unknown	N	RP	FL, Cr	M	NAp	D	B	D
Esterhazy K-1	IMC, Potash Corp. of Saskatchewan.	P	RP	FL, Cr	M	1962	C	C	D
Esterhazy K-2	...do	P	RP	FL, Cr	M	1967	C	B	D
Kalium	PPG Industries Canada Ltd.	P	SOL	Cr	M	1964	B	D	D
Lanigan Division	Potash Corp. of Saskatchewan	P	RP	FL, Cr	M	1968	C	D	D
Lockwood A	Unknown	N	RP	FL, Cr	M	NAp	D	B	C
Lockwood B	...do	N	RP	FL, Cr	M	NAp	D	B	C
McCauley	IMC	N	RP	FL, Cr	M	NAp	C	B	D
Patience Lake	Potash Co. of America	P	RP	FL, Cr	M	1958	D	A	C
Quill Lake (Kerr-McGee) A	Unknown	N	RP	FL, Cr	M	NAp	C	B	C
Quill Lake (Kerr-McGee) B	...do	N	RP	FL, Cr	M	NAp	C	B	C
Quill Lake (Scurry Rainbow) A	Potash Corp. of Saskatchewan	N	RP	FL, Cr	M	NAp	C	B	C
Quill Lake (Scurry Rainbow) B	...do	N	RP	FL, Cr	M	NAp	C	B	C
Rocanville Division	...do	P[11]	RP	FL, Cr	M	1971	C	B	D
Salt Springs	Denison Mines Ltd.	N	ICF	FL, Cr	M	NAp	D	B	C
Spy Hill	Unknown	N	RP	FL, Cr	M	NAp	C	B	C
Sussex	Potash Corp. of America	N	HCF	FL, Cr	M	1983	C	A	B
Vade	Cominco Ltd	P	RP	FL, Cr	M	1969	D	B	C
Whitewood	Unknown	N	RP	FL, Cr	M	NAp	B	B	C
Yorkton	...do	N	RP	FL, Cr	M	NAp	C	B	C
Young	...do	N	RP	FL, Cr	M	NAp	C	B	C
Zelma	...do	N	RP	FL, Cr	M	NAp	C	B	C
Chile: Salar de Atacama	Corfo	N	BR	FL	M	NAp	A	D	A
Congo: Holle	People's Republic of the Congo	N	RP	FL	M	([12])	D	A	B
France:									
Amelie	Mines de Potasse d'Alsace	P	LC	Cr	M	1914	B	B	B
Marie Louise	...do	P	RP	Cr	M	1914	B	C	D
Theodore	...do	P	RP	FL	M	1914	A	A	A
Germany, Federal Republic of:									
Bergmannssegen-Hugo/ Friedrichshall.[13]	Kali und Salz AG	P	SL	Cr	G	1930	A	A	A
Hattorf	...do	P	RP	Cr	G	1910	A	B	A
Neuhof-Ellers	...do	P	RP	FL	G	1956	A	B	A
Niedersachsen—Riedel	...do	P	SL	Cr	G	1910	A	A	A
Salzdetfurth	...do	P	SL	Cr	G	1900	A	A	A
Siegfried-Giesen	...do	P[14]	SL	Cr	G	1906	A	A	A
Sigmundshall	...do	P	SL	FL, Cr	G	1948	B	A	B
Wintershall	...do	P	RP	Cr	G	1903	A	C	A
Israel: Dead Sea Works	Dead Sea Works	P	BR	Cr	M	1952	A	D	D

See explanatory notes at end of table.

Table 11.—Potash mines and deposits included in the study, 1982—Continued

Country and deposit name	Owner	Status[1]	Mine method[2]	Mill method[3]	Potash product[4]	Initial year of production	Mill feed grade[5]	Mill capacity: Ore[6]	Mill capacity: Muriate product[7]
Italy:									
Corvillo	ISPEA	N	RP	FL	S	NAp	A	A	A[10]
Milena	EMS	N	RP	FL	S	NAp	A	A	A[10]
Pasquasia	ISPEA	P	RP	FL	S	1959	A	A	A[10]
Racalmuto	...do	P	RP	FL	S	1973	A	A	A[10]
Realmonte	EMSAMS	P	RP	FL	S	1976	A	A	A[10]
Jordan: Arab Potash	Arab Potash Co	P	BR	Cr	M	1982	A	D	D
Spain:									
Cardona	Unión Explosivos Rio Tinto S.A.	P	SL	FL	M	1930	A	A	A
Esparza	Potasas de Navarra S.A.	P	LC	FL	M	1963	A	A	A
Llobregat	Unión Explosivos Rio Tinto S.A.	P	RP	FL	M	1913	A	A	A
Suria	Minas de Potasas de Suria S.A.	P	RP	FL	M	1926	A	A	A
United Kingdom: Boulby	Cleveland Potash Ltd	P	RP	FL, Cr	M	1974	D	A	B

NAp Not applicable.
[1]P—producer, N—nonproducer, S—standby.
[2]RP—room and pillar, BR—brine recovery, SOL—solution mining, ICF—inclined cut and fill, HCF—horizontal cut and fill, LC—longwall caving, SL—sublevel.
[3]FL—flotation, Cr—crystallization, L—leach.
[4]M—potassium muriate, S—potassium sulfate, KMg—potassium-magnesium sulfate, G—potash operations in the Federal Republic of Germany produce muriate, sulfate, and numerous other potash products.
[5]Feed grade (weight percent K_2O): A—<15.0; B—15.0-20.0; C—20.1-25.0; D—>25.0.
[6]Mill ore capacity (thousand metric tons per year ore): A—<3,001-6,000; C—6,001-9,000; D—>9,000.
[7]Muriate product capacity (thousand metric tons per year muriate product): A—<500; B—501-1,000; C—1,001-1,500; D—>1,500.
[8]Grade and product capacity are for potassium-magnesium sulfate because the mine produces no muriate.
[9]Bonneville also produces manure salt.
[10]Grade and product capacity are for potassium sulfate since the mine produces no muriate.
[11]Rocanville flooded.
[12]Holle produced in the early 1970's.
[13]Friedrichshall Mine closed, reserves included with Bergmannaseghn-Hugo.
[14]Siegfried-Glesen shut down in 1984.

Khorat Plateau in Thailand was not evaluated because of lack of information about demonstrated resources of sylvinite. Carnallite resources are known but carnallite was not considered an ore in this study. The demonstrated resources of two California deposits, a producer at Searles Lake and a proposed operation at the Salton Sea were included in the resource totals discussed here, but the deposits were not included in the availability analysis because potash is or would be only a minor byproduct. Potash occurrences have been examined in Michigan by PPG but no resource data are available. The Silver Peak Lithium Mine in Nevada has potash, but it is not being recovered.

The 68 deposits included in this analysis contained demonstrated in situ potash resources of 11.7 billion mt K_2O equivalent, as shown in table 12 and figure 5. The table shows that 82 pct of demonstrated in situ resources in terms of contained K_2O equivalents are located in Canada, more than 10 pct in the Dead Sea, less than 4 pct in Western Europe, and less than 2 pct in the United States (it should be noted that the total demonstrated resources of K_2O in the United States almost double to 348 million mt when the byproduct resources of Searles Lake and the Salton Sea, 162 million mt, are included).

Table 12 also shows the percentage distribution of potash products. It shows that 89 pct of the potash potentially recoverable from resources located in market economy countries would take the form of potassium muriate, while 9 pct would be in the form of potassium sulfate.

Inferred resources are associated with many of the deposits included in this study. The largest are located in Canada. It has been estimated that Canadian inferred resources minable by conventional methods are 35 billion mt and that additional inferred tonnages of K_2O minable by solution methods are three times the amount minable by conventional underground methods (*11*).

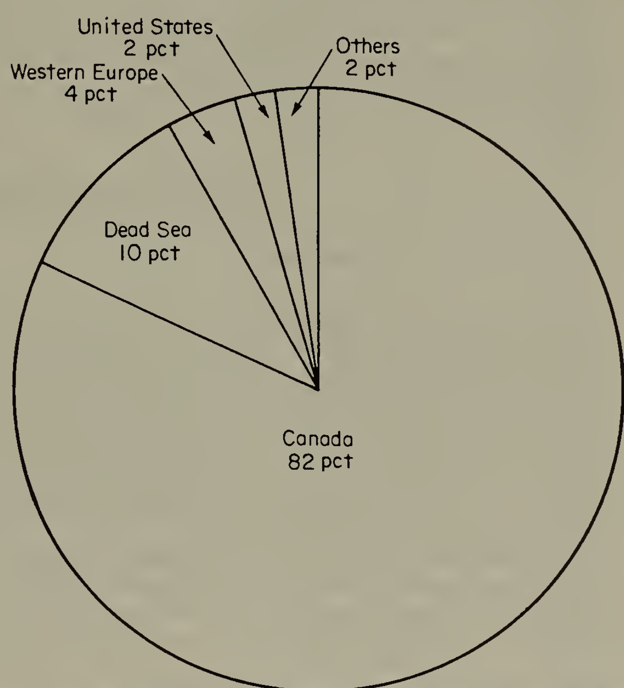

Figure 5.—Demonstrated in situ potash resources in market economy countries, 11.7 billion mt K_2O equivalents, 1984.

Table 12.—Demonstrated potash resources associated with deposits included in this analysis as of January 1984
(Quantities in million metric tons, grades in weight percent K_2O)

Geographic area	Grade, wt pct	In situ resources	In situ K_2O	Total[1] K_2O	Product share, wt pct of K_2O		
					Muriate[2]	Sulfate[3]	Other[4]
United States:							
New Mexico	12.78	853	109	72	80	6	14
Utah	.85	9,077	77	[5]77	4	96	([6])
Total or average[7]	1.87	9,930	186	149	41	52	7
Canada	22.50	42,788	9,630	2,978	100	0	0
Western Europe	12.10	3,546	429	227	50	25	25
Dead Sea	.75	164,968	1,237	[8]165	100	0	0
Other	7.27	3,040	221	23	86	14	0
Total or average	[9]5.22	224,272	11,703	3,542	89	9	2

[1]In recovered products.
[2]Minimum of 60 pct K_2O.
[3]Minimum of 50 pct K_2O.
[4]Other includes potassium-magnesium sulfate in New Mexico, manure salt in Utah, and the variety of products of the mines in the Federal Republic of Germany for Europe.
[5]In situ and recoverable K_2O are the same for Utah because the analysis assumed that all of the K_2O in the north arm of the Great Salt Lake would be recovered. As potash is recovered, more is brought in by streams and when the brine becomes less concentrated, previously precipitated salts on the lake bottom would be redissolved.
[6]Less than 0.5 pct.
[7]Does not include the 162 million mt of K_2O equivalent at Searles Lake and the Salton Sea which could be produced as a byproduct.
[8]K_2O in the product is much lower than in situ K_2O because the analysis is based on a 25-pct recovery. After 25 pct is taken from the Dead Sea, the grade of the remaining brine would be too low to make recovery economic.
[9]Includes both ore and brine, average grade is 20.7 pct for ore and 0.75 pct for brine.

GEOLOGY

Potassium and sodium are common elements found in most rocks. Feldspars and micas contain varying amounts of potassium. When these minerals weather they release potassium ions. The ions are absorbed into the soil and into plants or are transported through rivers to the sea. Potash layers are often interbedded with halite (sodium chloride) because of the precipitation of sodium from these same solutions. The formation of potassium-bearing deposits is usually a result of cyclic precipitation of potassium compounds during evaporation of solutions.

Occasionally in geologic history parts of an ocean became landlocked. When this was followed by arid conditions, these segregated seas were subjected to evaporation, and halite beds began to form. Eventually, if the brine became sufficiently concentrated, the highly soluble potassium salts began to precipitate. If wet periods occurred, the salinity of the sea would decrease which caused sylvinite precipitation to cease and halite precipitation to begin again. This cycle could repeat many times, or begin again with more marine brines being added to these segregated seas. When the sea finally dried, a halite body interbedded with sylvinite layers remained.

Today, areas that have this geologic history account for most of the profitably mined resources in the world. In some cases, such as the Dead Sea and the Great Salt Lake of Utah, brines containing recoverable amounts of potassium are also exploited.

A detailed discussion of the geology of the deposits that were evaluated as a part of this study is presented in the appendix.

MINING AND PROCESSING OF POTASH

MINING

Eighty percent of the potential annual production of potassium muriate from producing mines included in this study could be recovered by conventional underground mining methods, 8 pct could be from underground solution methods, and 12 pct could be recovered from surface brine operations. Producing potassium sulfate operations would derive 91 pct of potential annual production from underground ores recovered using conventional methods, with the remaining 9 pct from brine recovery.

Individual deposit or operation information such as mining and beneficiation methods, status, capacities, grades, ownership, and initial production year are shown in table 11.

Conventional Underground Mining Methods

Most potash occurs in deposits that require recovery by underground mining methods. Room and pillar is the most common method used. However, potash recovery using longwall mining techniques is common in France and Spain, and potash operations in the Federal Republic of Germany use sublevel techniques where the seams are steeply dipping because of extensive folding.

Table 13 shows the weighted average in situ grade, mine recovery, and annual capacity for mines using conventional underground methods. This table shows that Canadian mines have the highest in situ grade, but the lowest mine recovery. The low mine recovery results because large

Table 13.—In situ grade and mine recovery for potash mines using conventional underground methods, by area

Area	In situ grade, pct	Mine recovery, pct	Annual capacity, 10^6 mt ore
Producers:			
United States	13.1	88.7	18
Canada	25.7	36.7	47
Europe	12.4	62.1	51
Weighted average or total	21.5	62.1	116
Nonproducers:			
United States	11.5	88.3	10
Canada	24.0	35.7	78
Other[1]	18.2	34.1	6
Weighted average or total	23.6	35.9	94

[1]Italy, Brazil, and Congo.

pillars are left because of the depth of most of the Canadian ore and the need to avoid any subsidence of overlying water-bearing formations. When the ore body is situated greater than 1,000 m below the surface, conventional methods cannot be used because of rock stability problems. Solution mining techniques have been successfully practiced in these situations. These methods are discussed later in this section.

Room and Pillar

As of January 1982, 25 of the 41 producing potash mines included in this analysis utilized room and pillar recovery methods. Additionally, 24 of 27 developing properties have proposed room and pillar operations.

Room and pillar mining is used when the ore body is flat to shallow dipping. Access to the ore body is typically by means of a vertical shaft. The method involves driving openings that divide the potash ore into rectangular blocks of ore, leaving pillars between the blocks for support. In shallow mine depths, such as those in New Mexico, the pillars are then recovered as mining in an area is completed (pillar retreat) allowing the back (roof) to cave in. Total mine recovery when pillars are recovered is up to 90 pct. However, in deep mines, such as those in Canada, pillars must remain in place for support during the entire life of the mine. Because of this, room and pillar mine recoveries in Canada are near 35 pct. The pillars cannot be recovered from the Canadian mines because the brines under high pressure in the Blairmore Formation above the potash would flood the mine.

Room and pillar mining allows operators to modify the system in ways that are suitable to their specific operation. It also allows for a large degree of selectivity, an important factor when a barren area, called a "salt horse," occurs in the ore body.

Sublevel Stoping

Sublevel stoping is common in steeply dipping deposits that are surrounded with competent country rock. Six producing mines utilize this method. Access to these mines is generally by vertical shaft. Ore is mined by drilling and blasting on each sublevel and allowing the ore to fall into drawpoints located below the ore body. This method is ideal for mining potash that is generally uniform in grade, since sublevel stoping does not lend itself to sorting of the ore. Mine recoveries using this method average 75 pct.

Longwall Caving

Longwall mining is a highly productive but capital intensive mining method used in flat-lying deposits that have relatively weak overlying strata. Four producing mines utilize this method. The ore is cut from a long face, usually greater than 50 m in length, by a cutting drum, known as a face shearer. The broken ore drops onto a conveyor running parallel to the face. The potash is transferred to another conveyor, running perpendicular to the face which transports the ore to the surface for processing. Roof support chocks keep the roof from caving in at the face, allowing working room for the personnel and equipment. As the face advances, the roof support chocks and conveyor are advanced, allowing the roof to cave behind the chocks. France uses this method exclusively and Spain used this technique in its Esparza Mine until it closed.

Cut-and-Fill Stoping

Cut-and-fill stoping was not used in the potash industry until recently. It is the method at Salt Springs and Sussex—two developing mines in New Brunswick, Canada. In this method, the ore is broken by overhand mining techniques (similar to sublevel stoping) and removed from the stope. After the broken ore is removed, the stope is filled with waste to within working distance of the back and the process is repeated. The waste material will be mostly common salt, halite. This method is suitable in the New Brunswick area because storage of mill tailings on the surface poses a problem. Mine recovery for this method is expected to be about 75 pct.

Solution Mining

The Kalium Mine in Canada and the Cane Creek Mine in Utah are the only potash mines using underground solution methods that involve pumping liquids underground to dissolve the potash and bring it to the surface through wells as a brine. The potash deposit being explored in Michigan would be developed using this method.

The Kalium ore body occurs at depths greater than 1,000 m. At this depth, the use of conventional mining methods becomes inadequate because of rock instability caused by the high pressure of the overlying rock. Although the system used in Kalium is confidential, documented patents reveal that a hot water process is used.

For the Kalium method to be successful, the deposit must be overlain by an impermeable layer (in this case, halite). The process involves developing a well by sinking a casing and tubing just below the potash horizon. A cavity is then developed by continuously pumping hot water through the pipe annulus and allowing the salt solution to rise up the tubing to the surface. The concentrated brine is then pumped to the mill plant for potash recovery. This method requires continuous development of new wells. Although this method has been tried elsewhere (i.e., Southwest Potash Corp., Yorkton, Saskatchewan, Canada) (*12*), it has only been successful at Kalium.

The Cane Creek Mine was originally developed as a conventional underground room and pillar mine. Problems were encountered as a result of high rock pressures; a pitched, faulted, and undulating potash bed; weak roof conditions; and gas in the mine. As a result, the mine was converted to a solution operation. This was done by flooding

the underground operation. Water is pumped into the mine as brine is withdrawn. It takes from 300 to 350 days retention time to produce satisfactory brine. As the brine becomes saturated, it moves to the lowest level of the former workings; at this level a large well extracts the brine. The brine is pumped to solar evaporation ponds.

Brine Recovery

Four established and one proposed operation that produce or would produce potash from naturally occurring brines are included in the availability analysis. One operation recovers potash from the brines of the Great Salt Lake in Utah, and two operations recover potash from the brine of the Dead Sea; one in Israel and the other in Jordan. At the fourth established operation, potash-rich brines are recovered from a shallow aquifer at Wendover, UT, using 6-m-deep trenches. The proposed operation, located in Chile, would recover underground brines through shallow wells from the Salar de Atacama deposit in Chile. All of these brine operations incorporate solar evaporation ponds in their recovery process.

Solar evaporation depends on the heat of the sun to evaporate the water, thus concentrating the mineral content of brines. This type of system is best utilized in dry regions such as the Dead Sea region of Israel and Jordan, and the Great Salt Lake and the Bonneville Salt Flats of Utah.

Solar evaporation systems vary in detail. In a typical system, brine is pumped into shallow solar evaporation pans ranging in size from 2 to 80 km^2, where the water is evaporated from the brine. Some areas also use chemicals such as "napthol green" to increase the evaporation rate. At the Dead Sea, when the brine reaches a specific gravity of 1.30, it is pumped into carnallite pans. Further evaporation in the carnallite pans, which operate on a batch system, yields carnallite and other products. The evaporate is harvested every 2 or 3 yr, or when the specific gravity reaches 1.35, by a dredge and fed to the mill plant. The unused brine (after processing) is usually pumped back to its origin.

BENEFICIATION

Potash ore must be beneficiated to remove halite and clay insolubles before it can be sold as a marketable product. Potash ore is usually beneficiated by flotation or crystallization, or a combination of both; langbienite ore is beneficiated only by washing (leaching). Table 14 shows the weighted average mill recoveries.

Table 14.—Weighted average mill recovery for mills beneficiating potash ore and proposed recovery rates for nonproducing mills, by area, percent

Producers:	
United States	75.1
Canada	85.5
Europe	95.9
Weighted average	91.6
Nonproducers:	
United States	74.5
Canada	87.8
Brazil and Congo	88.1
Weighted average	87.7

Potash ore from the mine is first sent to a crushing and screening circuit where the potash minerals are liberated from the gangue minerals. Generally, the ore passes through a series of vibrating screens to classify oversize and undersize particles. Undersize particles are passed to the next processing stage. Oversize particles are returned to the crushing circuit, usually impactors, for further size reduction and are then rescreened. For most potash ores the undersized material goes to the scrubbers; however, the undersized material in the processing of langbeinite ore is leached, to remove the sodium chloride contaminant, thus leaving the washed langbeinite to be dried and screened.

Crushed ore is passed through scrubbers where trommels or water jets are used to remove any clay or similar material that is exposed by crushing the ore. Desliming, typically utilizing hydrocyclones, is an especially important step prior to flotation, to prevent ultrafine particles from entering the flotation cells. These fine particles have a tendency to cement together and greatly reduce the efficiency of flotation cells. Desliming is not necessary prior to crystallization; however, it is often used to provide a clearer solution in the evaporator and aid in nucleation.

Flotation

Flotation is used in the beneficiation of sylvinite and kainite ores; a simplifed flotation circuit is shown in figure 6. In the case of sylvinite ores, after the ore has been deslimed, reagents are added to prepare the ore for flotation.

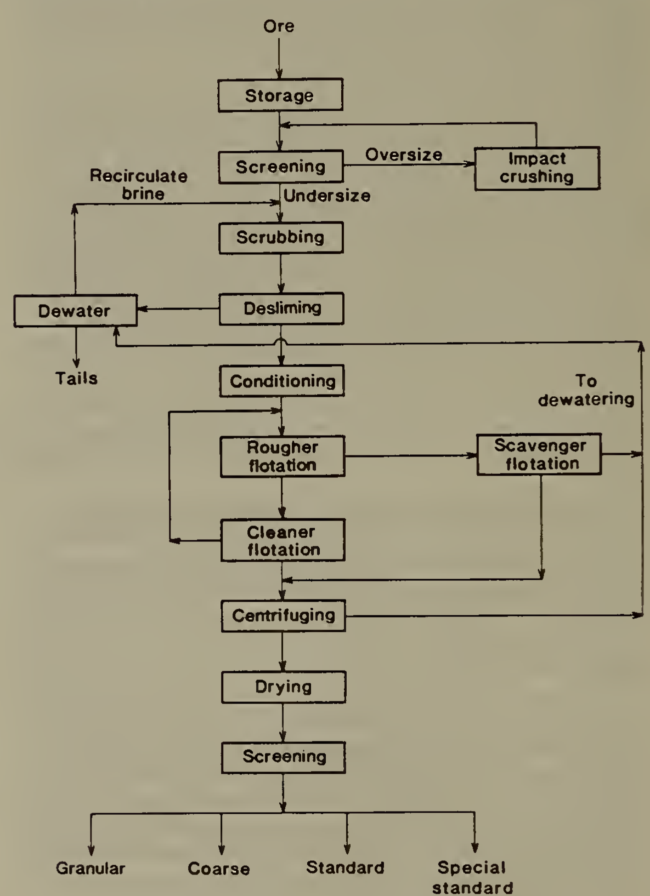

Figure 6.—Simplified flotation circuit.

Reagents include a depressant for slimes, an amine sylvite (KCl) collector, flotation oil frother, and anticaking chemicals.

The primary function of flotation of sylvite is to separate, by means of reagents, the potassium chloride from the sodium chloride and to concentrate the potassium to marketable levels. Flotation also acts to separate the potash from clays and other minerals and insolubles that may exist in the feed. Many mills that recover sylvite by flotation include a crystallization step after flotation to increase the recovery of fines. Those that only use flotation include more cleaning circuits to achieve the same recovery and product grade results.

Flotation of kainite is similar to the flotation of sylvite. Kainite is separated from the waste material by flotation. After flotation the kainite goes through a conversion process, in which it is dissolved in a sulfate solution producing schoenite, and a lixiviation step, in which the $MgSO_4$ is dissolved from the schoenite leaving K_2SO_4. The only operations included in this study that process kainite are located in Utah and Italy.

Crystallization

Crystallization is a thermal process used to recover potash from a saturated solution of KCl (liquor). A simplified crystallization circuit is shown in figure 7. The liquor is pumped through a heat exchanger and then into an evaporative crystallizer. In the crystallizer, the surface of the slurry is maintained at the boiling point of water, and evolved steam is withdrawn through the top of the unit and subsequently condensed. In order to maintain equilibrium, the dissolved KCl nucleates on the surface of KCl crystals already existing in the circulating stream. When the crystals have grown sufficiently, the slurry is removed from the circulating stream. The slurry then goes to a centrifuge for dewatering. The solids are then dried and sized. If combined methods are used, the solids are combined with the concentrate from the flotation cells. From this point drying and sizing is performed on a common product.

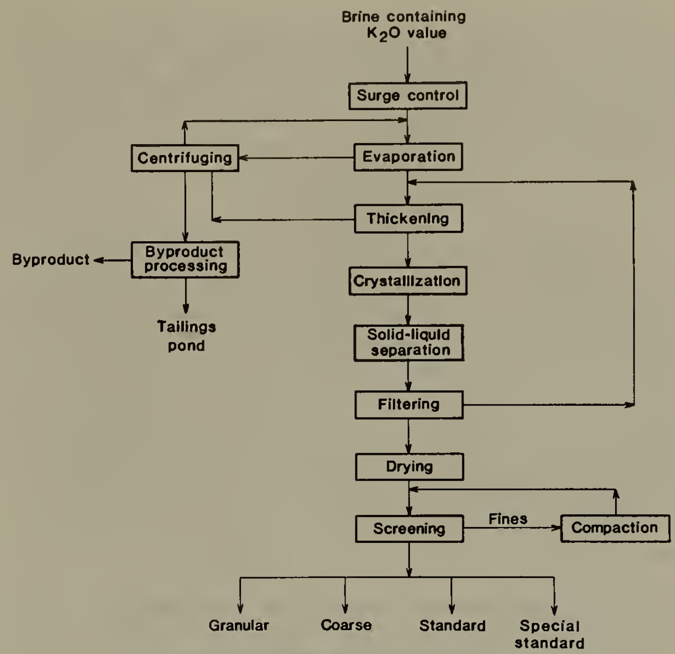

Figure 7.—Simplified crystallization circuit.

Drying and Sizing

The floated or crystallized product is dried to remove as much water as possible from the product to reduce transportation costs and to allow sizing. Fluid bed or rotary dryers are used.

Sizing via screens is performed after all other beneficiation is completed. The value of potash is dependent on its size. The common sizes are granular, coarse, standard, and special standard. The value follows accordingly with granular sized potash having the highest worth. Sometimes the dried potash is compacted and then crushed and screened to produce a granular product.

POTASH DEPOSIT PRODUCTION COSTS

COSTING METHODOLOGY

For each property included in this study, a cost evaluation was made for both capital and operating costs, to reflect as nearly as possible, actual operations, or in the case of nonproducers, to reflect expected operational technologies and capacities. Costs for the deposits in the United States were developed by Bureau of Mines Field Oeprations Centers in Spokane, WA, and Denver, CO, based on actual reported company data, scaling from simlar known operations, or by using the Minerals Availability Program (MAP) cost estimating system (CES) (*13*). Costs for most foreign deposits were collected and developed by Jacobs Engineering Group, Inc., under a contract with the Bureau of Mines. Some of the foreign deposit costs are actual company reported data; others were estimated by the contractor using their knowledge of the operation or deposit plus their experience in the industry.

All costs presented in this report, with the exception of those for the Dead Sea Works in Israel, are in terms of January 1984 U.S. dollars. The cost estimates reflect a prefeasibility estimate of ±25 pct. Costs associated with the Dead Sea Works in Israel have not been updated from the original January 1982 U.S. dollars collected by Jacobs Engineering Group, Inc. This is because inflation and the extreme devaluation of Israeli currency between 1982 and 1984 make the updating of costs to January 1984 unrealistic. This does not seriously affect the analysis of the availability of potash from Israel.

Capital expenditures were calculated for exploration, acquisition, development, mine plant and equipment, construction of the mill plant, and installation of the mill equipment. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, engineering design, facilities and utilities, and working capital. Facilities and utilities (infrastructure) includes the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance.

Mine and mill operating costs are a combination of direct and indirect costs. Direct operating costs include materials, utilities, direct and maintenance labor, and payroll overhead. Indirect operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research.

OPERATING COSTS

Operating costs for underground mines included in this study that use conventional mining methods to produce potassium muriate are shown by geographic area in tables 15 and 16. Table 15 shows mine and mill costs per metric ton ore, and ore feed grade. Table 16 shows costs per metric ton potassium muriate product for all operating costs. Canadian properties have the lowest mine and mill operating costs both in terms of dollars per metric ton ore, and in terms of dollars per metric ton muriate. This reflects the fact that ore grades in Canada are high relative to other areas.

Mine operating costs per metric ton of ore for producing mines in the United States are slightly lower than those for mines in Europe. Mine operating costs in Europe in terms of dollars per metric ton muriate, are much higher because many other products in addition to muriate are produced from the ore. Costs for U.S. nonproducers are higher than for producers, both in terms of dollars per metric ton ore and dollars per metric ton muriate product. They are higher than the average mine operating costs for European producers both in terms of dollars per metric ton ore and dollars per metric ton muriate product.

Mill operating costs per metric ton of ore for producers in the United States are lower than all other areas except Canada. Nonproducers in the United States would have higher mill operating costs than producers in the United States and Canadian producers and nonproducers and lower mill operating costs than European producers. Mill operating costs per metric ton of ore and per metric ton of product for mines in Europe are much higher than others in the analysis, owing to the many byproducts produced. In terms of dollars per metric ton, muriate product, European producers have the lowest costs except for producers in Canada, followed in order by producers and nonproducers in the United States.

The column labeled "taxes" in table 16 includes property, local, national, and severance taxes, plus royalties, if any. Taxes are generally greater for nonproducers in this study, because in most cases, the revenues required to cover the higher overall costs (including profit) are greater. In other words, nonproducers would require a higher taxable income (leading to higher tax payments) in order to cover all operating costs and provide for a 15-pct DCFROR on all investments. Total operating cost for muriate f.o.b. mill represents the total operating cost at the mill per ton of muriate. It does not include any transportation cost.

Byproduct revenues are the revenues received for products other than the primary product. They are calculated by multiplying the quantity of each byproduct produced by its market price. They must be deducted from total

Table 15.—Mine and mill operating costs per metric ton ore for selected underground potassium muriate mines and deposits

(All costs are in January 1984 dollars per metric ton ore on a weighted-average basis)

	Number	Feed grade, wt pct K_2O	Operating costs: Mine	Operating costs: Mill
United States:				
Producers	6	13.4	$5.20	$5.70
Nonproducers	3	11.5	6.90	6.80
Canada:				
Producers	9	21.0	3.40	4.70
Nonproducers	18	23.0	4.00	4.50
Europe[1]	16	11.6	5.70	10.00

[1]Includes the Federal Republic of Germany, France, Spain, and the United Kingdom.

Table 16.—Operating costs per metric ton potassium muriate product for selected underground mines and deposits

(All costs are in January 1984 dollars per metric ton product on a weighted-average basis)

Country or region	Number	Mine	Mill	Taxes[1]	Total operating cost (f.o.b. mill[2])	Byproduct revenues[3]	Total operating cost for muriate[4]	Transportation cost to point of export or domestic market[5]	Total cost including transportation for muriate[6]	Total cost for muriate[7]
United States:										
Producer	6	$38.70	$42.50	$8.00	$89.20	$34.70	$54.50	$49.00	$103.50	$115.00
Nonproducer	6	72.00	71.60	26.30	169.90	94.00	75.90	49.00	124.90	184.60
Canada:										
Producer	9	10.10	13.90	8.80	32.80	.00	32.80	32.20	65.00	75.30
Nonproducer	18	12.20	13.50	142.30	168.00	.00	168.00	28.80	196.80	248.60
Europe:[8] Producer	16	63.80	111.90	26.20	201.40	[9]158.58	43.40	3.20	46.60	81.61

[1]Includes all property, local, national, and severance taxes plus any royalty. Nonproducers would require higher income in order to provide the stipulated 15-pct DCFROR; thus, aggregate tax payments are generally higher than for producing operations.
[2]Sum of the 3 previous columns, mine and mill operating costs, and taxes.
[3]Calculated by multiplying the quantity of each byproduct by its market price.
[4]Operating cost f.o.b. mill; calculated by deducting byproduct credits from total operating costs f.o.b. mill.
[5]Cost to selected points of export or domestic markets that have been assumed as the product destination points for this study.
[6]Total muriate operating cost at the port or market; calculated from total operating cost, f.o.b. mill, by deducting byproduct credits, and adding the cost of transportation.
[7]Includes a 15-pct DCFROR on all investments over the life of the property.
[8]Europe includes the Federal Republic of Germany, France, Spain, and the United Kingdom.
[9]Byproduct revenues are large because of the numerous potash products produced in addition to muriate.

operating costs to determine the costs of producing the primary product.

Transportation costs represent the average cost to transport the muriate product to a port or domestic market. The transportation cost for the operations in the United States represents the cost of shipping by rail from the Carlsbad, NM, area to a typical market in the central Midwest. For other countries, the transportation cost represents the cost to ship to a port or a point of export. The table shows transportation costs to be highest for mines in the United States. The total cost to transport potash from Saskatchewan to the central part of the United States (Missouri) in 1984 is estimated to be $33/mt. The total transportation cost for mines in the United States to the same point was $49/mt. Canadian producers appear to have a transportation advantage in the northern States and domestic producers appear to have an advantage in the southern States. Shipments to the central Midwest have shifted. In 1980, domestic producers shipped 94,000 mt to Missouri but in 1983, Missouri received no domestic shipments, but received significant shipments from Canada (*14*).

European operations are much closer to the port or market and therefore have lower transportation costs. Total operating costs for muriate represent all operating costs including transportation to port or market less byproduct revenues. This represents the operating costs attributable to muriate. The last column on table 16 represents the total cost attributable to muriate including recovery of capital and a 15-pct DCFROR on all investments over the life of the property.

CAPITAL COSTS

Total primary investments to develop new underground muriate mines in 1984 in Canada are estimated to range between $200 and $800 million U.S. dollars. On an annual metric ton muriate product basis, the range is estimated to be generally between $220 and $340. Total primary investments to develop a new underground operation in the United States are estimated to range between $50 and $150 million, which, on an annual metric ton muriate basis become $100 to $150. Total primary investments to develop new underground muriate mines in Brazil and the Congo are estimated to be generally less than those in Canada and larger than those in the United States. On an annual metric ton ore basis primary investments to develop new underground muriate mines in Brazil and the Congo are estimated to be generally above those of Canada. These costs represent the costs to acquire, explore, develop, and equip a new mine site along with construction of mine and mill plants and buildings.

The reason total primary investments are larger in Canada is because the mines are larger and shafts are deeper and more difficult to sink. Primary investments per metric ton of muriate in Canadian operations are higher than those in the United States because the Canadian ore is at more than twice the depth as ore in the United States and serious problems occur during shaft sinking. Developing the deposits in Brazil or the Congo is more difficult geologically than developing deposits in the United States, which results in higher initial investments for mines in those countries.

POTASH CONCENTRATE AVAILABILITY

ECONOMIC EVALUATION METHODOLOGY

Once all the cost and engineering data are established, production parameters and cost estimates for each mine and deposit are entered into the MAP computerized supply analysis model (SAM). The Bureau has developed the SAM to perform DCFROR analyses to determine the long-run constant dollar cost. This cost of the primary commodity must equal the price at which the primary commodity must be sold to recover all costs of production and investments (*15*). The DCFROR is most commonly defined as the rate of return that makes the present worth of cash flow from an investment equal to the present worth of all after-tax investments (*16*). For this study, a 15-pct DCFROR was considered the necessary rate of return to cover the opportunity cost of capital plus risk. The determined value for the primary commodity cost is equivalent to the average total cost of production (including credits for byproducts) for the operation over its producing life.

If an operation has more than one product, the prices of the byproducts are assumed to be the market prices for the period of analysis, which, for this study, is January 1984. Revenues generated by byproducts are credited against the costs of production. Market prices used in this analysis are shown in table 17.

All prices in this table have been converted to U.S. dollars per metric ton. The original price data for commodities in the United States or Canada were from the Chemical Marketing Reporter or Green Markets. The muriate prices for both the United States and Canada are based on prices for coarse muriate from the January 9, 1984, Green Markets. Coarse muriate prices in the January 10, 1983, Green Markets for the United States (f.o.b. Carlsbad, NM), and for Canada (f.o.b. Saskatchewan), were not significantly different than the January 1984 prices shown in table 17. The original price data for commodities in the Federal Republic of Germany (FRG) were supplied by Kali und Salz (K&S), the company that owns the potash mines in the FRG. The prices supplied by K&S were in the currency of the FRG.

The percentage distribution of total revenues projected to be received by operations for potash products at January 1984 market prices is shown in table 18. These percentages were developed by multiplying the estimated quantity of each potash product produced over the life of the mine and using the January 1984 price to estimate the revenues generated. The percent of revenues from each product was then calculated.

Table 18 shows that 86 pct of the revenues estimated to be generated by potash products from the 68 mines and deposits included in this analysis would be generated by muriate of potash. Some areas shown, such as Utah and Europe, are projected to generate significant revenues from potassium sulfate but, overall, sulfate is expected to account for only 10 pct of the revenue. Potash products other than 60 pct K_2O muriate and potassium sulfate contribute 41 pct of the revenue of FRG potash operations.

Based on the MAP methodology, all capital investments incurred earlier than 15 yr before the initial year of the analysis (January 1984) are treated as sunk costs. Capital

Table 17.—Market prices per metric ton for selected potassium products and related minerals for January 1984, f.o.b. mill

Commodity	Where applicable	Grade, wt pct K_2O	Price, $/mt
Potash products:			
Muriate, coarse	United States, Carlsbad	62	[1]175.52
Do	Canada, Saskatchewan	62	[1]168.90
Muriate	Federal Republic of Germany[2]	50	106.50
Do	...do[2]	40	82.40
Sulfate	United States	50	181.00
Do	Federal Republic of Germany[2]	50	146.00
Potassium-magnesium sulfate.	United States	22	65.00
Manure salt	...do	19	[e]20.00
Korn kali	Federal Republic Germany[2]	40	99.82
Patent kali	...do[2]	32	141.27
Kali magnesia	...do[2]	28	141.27
Thomas kali	...do[2]	18	[e]80.00
Raw salts	...do[2]	19	[e]40.00
Magnesia kainit	...do[2]	12	46.34
Other products:			
Table salt	United States	NA	50.00
Sodium sulfate	...do	NA	99.20
Bromine	Federal Republic of Germany[2]	NA	727.00
Epsom salt	...do	NA	52.00
Kieserite	...do	NA	52.00
Magnesium chloride	United States	NA	64.00
Do	Federal Republic of Germany[2]	NA	64.00
Magnesium chloride solution.	...do	NA	25.00

[e]Estimated. NA Not available.
[1]Based on prices published by Green Markets, January 9, 1984.
[2]Prices include the cost of delivery in the Federal Republic of Germany and are not f.o.b. mill prices.

Sources: Private communication from Kali und Salz, Federal Republic of Germany, and estimated by authors, and from references 17 and 18.

Table 18.—Distribution of revenues received by potash operations at January 1984 market prices, percent

Area	Number	Muriate	Sulfate	Other[1]
United States:				
New Mexico	10	63	12	25
Utah	3	1	99	(2)
Total or average	13	20	72	8
Canada	28	100	0	0
Europe:				
Federal Republic of Germany	8	30	29	41
Other Europe[3]	13	56	44	0
Dead Sea	2	100	0	0
Other[4]	4	88	12	0
Total or average	68	86	10	4

[1]Includes potassium-magnesium sulfate and manure salt in the United States and many potash products other than 60 pct K_2O muriate and potassium sulfate in the Federal Republic of Germany.
[2]Less than 0.5 pct.
[3]Includes operations in France, Italy, Spain, and the United Kingdom.
[4]Includes Brazil, Chile, and the Congo.

investments incurred less than 15 yr before January 1984 have the estimated undepreciated balance carried foward to January 1984, with all subsequent investments reported in constant January 1984 dollar terms. All reinvestment, operating, and transportation costs are expressed in January 1984 dollars. No escalation of either costs or prices was included because it was assumed that any increase in costs would be offset by an increase in market price of the commodities.

The SAM contains a separate tax-records file for each State or nation which includes all the relevant tax parameters such as corporate income taxes, property taxes, royalties, severance taxes, or other taxes that pertain to the production of potash under which a mining firm would operate. These tax parameters are applied against each mineral deposit under evaluation with the implicit assumption that each deposit represents a separate corporate entity. Other charges considered in the analysis include standard deductibles such as depreciation, depletion, deferred expenses, investment tax credits, and tax-loss carryforwards. The system also contains an additional file of economic indexes to allow for updating of all cost estimates to the base date (January 1984 for this study).

Detailed cash-flow analyses are generated by the SAM for each preproduction and production year of an operation beginning with the initial year of the analysis. Upon completion of the analyses for each mine and deposit, all properties included in the study were simultaneously analyzed and aggregated into total and annual resource availability curves. The total resource availability curve is a tonnage-cost relationship that shows the total quantity of recoverable potash product potentially available at each operation's average total cost of production over the life of the mine, determined at the stipulated (15 pct) DCFROR. Thus, the curve is an aggregation of the total potential quantity of potash that could be produced over the entire producing life of each operation, ordered from operations with the lowest average total cost of production to those with the highest. The curve provides a concise, easy-to-read, graphic analysis of the comparative costs associated with any given level of potential output and provides an estimate

of what the average long-run price of potash (in January 1984 dollars) would likely have to be in order for a given tonnage to be potentially available to the marketplace. Costs reflect not only capital and operating costs, but also credit for byproducts, all pertinent taxation, and the cost of transporting the product to the nearest port or domestic point of consumption.

Annual curves are a disaggregation of the total curve to show annual potash availability at varying costs of production. Each curve represents a specific cost level. The horizontal axis represents time, either actual years for producers, or the number of years following the commencement of development for nonproducing operations. The vertical axis represents the annual production level based upon aggregation of the proposed capacities of each individual property.

Certain assumptions are inherent in all the curves. First, all deposits produce at full operating capacity throughout the productive life of the deposit. Second, each operation is able to sell all of its byproducts at the stipulated prices and all of its primary product at a price sufficient to generate total revenues equal to or greater than its average total production cost. Third, development of each nonproducing deposit began in the same base year (N) (unless the property was developing at the time of the evaluation). Since it is difficult to predict when the explored deposits are going to be developed, this assumption was necessary in order to illustrate the maximum potential availability with a minimum lag time. It is doubtful, however, that this potential would be reached in the short term since it is unlikely all new producers would start preproduction in the same year. The preproduction period allows for only the minimum engineering and construction period necessary to initiate production under the proposed development plan. Consequently, the additional time lags and potential costs involved in filing environmental impact statements, receiving required permits, financing, etc., have been minimized in the individual deposit analyses.

For this study, separate discussions and analyses were performed for each potassium product (potassium muriate, potassium sulfate, and potassium-magnesium sulfate) in order to correctly represent the availability of potash.

TOTAL AVAILABILITY

Muriate of Potash

Sixty-one properties analyzed in this study produce or are proposed to produce muriate of potash (KCl). They could recover 5,512 million mt muriate of potash with a minimum grade of 60 pct K_2O, containing 3,400 million mt K_2O equivalents (table 19, fig. 8). These resources were generally the only product that would potentially be produced at these operations although a small number of operations recover or could recover other potassium and nonpotassium minerals.

The table shows 4,848 million mt potentially recoverable from properties in Canada. This is 88 pct of the

Table 19.—Total estimated recoverable muriate of potash, 60 pct K_2O, in 1984, million metric tons

Country or region	Producing mines	Nonproducing deposits	Total
United States	84	17	101
Canada	2,596	2,252	4,848
Western Europe and the Dead Sea	458	0	458
Brazil, Chile, and the Congo	0	105	105
Total	3,138	2,374	5,512

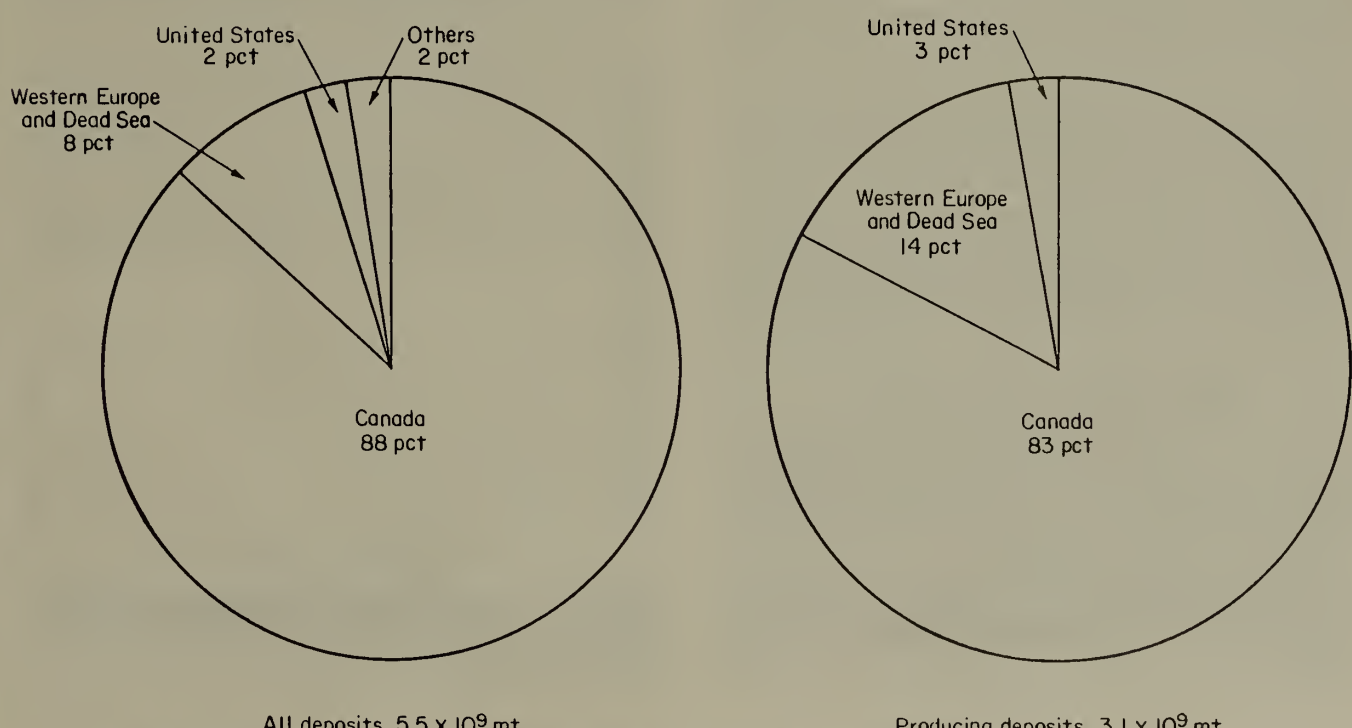

Figure 8.—Estimated potentially recoverable muriate of potash, 60 pct K_2O, associated with analyzed deposits.

total potentially recoverable muriate from all properties analyzed in this study. Producing mines located in Europe and near the Dead Sea (Israel and Jordan), could recover 458 million mt of KCl which is more than 8 pct of the total. Recoverable KCl in the United States was 101 million mt, only 2 pct of the total and KCl potentially recoverable from nonproducing deposits located in Chile, Brazil, and the Congo was 105 million mt, also 2 pct of the total.

Figure 9 shows the total muriate cost-tonnage relationships for all mines and deposits in market economy countries included in this analysis. This figure illustrates the tonnage of KCl that could be recovered and shipped to a port or domestic market at costs less than $250/mt, these costs include a 15-pct rate of return on invested capital. More than 4 billion mt of muriate could be potentially recovered at costs less than $250/mt and more than 3 billion mt of muriate could be potentially recovered at costs less than $110/mt. At $80/mt, approximately 1.4 billion mt of muriate could be potentially recovered, which is only 25 pct of the total muriate potentially recoverable from properties included in this study. A closer analysis will be presented of key countries producing muriate and relating the cost of production to the appropriate price of potash for that area. The total muriate cost-tonnage relationships for producing and nonproducing operations in Canada are both shown in figure 10.

The January 1984 price, f.o.b. Saskatchewan, was approximately $69/mt for coarse muriate. The costs in figure 10 include the cost of transporting the muriate product to a point of export. This transportation cost for each mine or deposit is based on where the product is exported. The weighted average cost per metric ton to a point of export is approximately $32 for producing operations and $29 for nonproducing operations. To compare the market price f.o.b. mill to the costs on the curve, the transportation cost must be added to the f.o.b. market price. The tonnage that could potentially be recovered from producing mines at a cost comparable with the 1984 market price plus transportation, approximately $110/mt product, would 2,555 million mt. This is more than 98 pct of the total tonnage that could potentially be recovered from Canadian producing mines and shows that producing mines in Canada are viable operations. Approximately 37 pct, 955 million mt, could be recovered at costs less than $80/mt, which is significantly below 1984 market price.

The total muriate cost-tonnage relationship for nonproducing potash properties in Canada shows that almost 1,000 million mt potassium muriate could potentially be recovered from nonproducing Canadian properties at costs plus transportation less than $250/mt. An additional 1,250 million mt is potentially recoverable at costs greater than $250/mt, and is therefore not shown in figure 10 but is included in the total recoverable muriate in table 19. At costs less than the 1984 market price plus transportation, $110/mt, very little potash could be recovered from these nonproducing deposits. This implies that without increased prices little incentive will exist for new production development of potash properties.

Figure 11 shows the total muriate cost-tonnage relationship for all Canadian mines both with the costs f.o.b. mill and with cost including the transportation cost to the point of export.

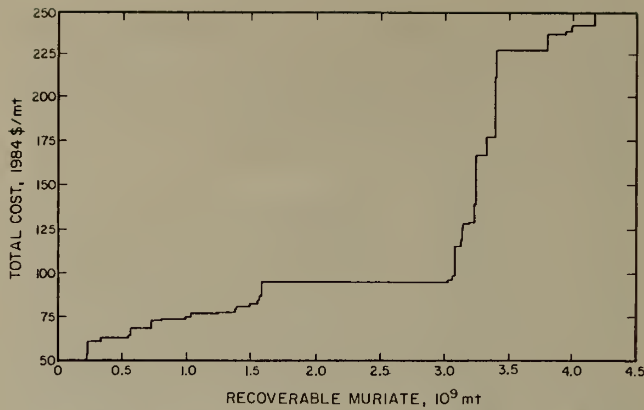

Figure 9.—Muriate potentially recoverable from mines and deposits in market economy countries.

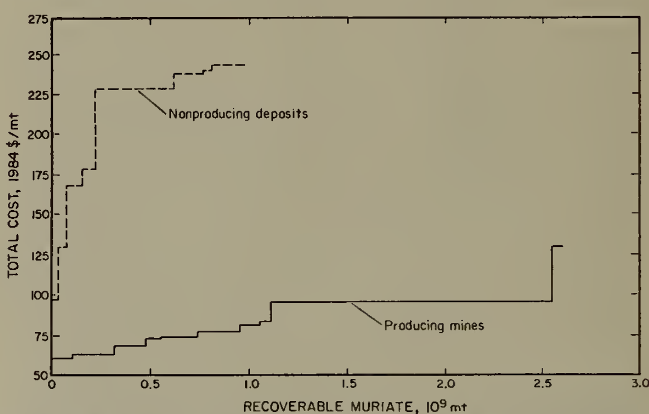

Figure 10.—Muriate potentially recoverable from producing mines and nonproducing deposits in Canada.

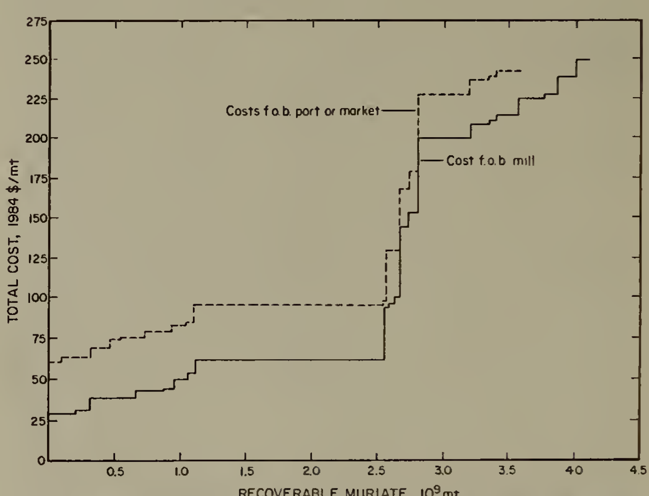

Figure 11.—Muriate potentially recoverable from mines and deposits in Canada, related to both f.o.b. mill costs and to costs including transportation.

Potentially recoverable muriate for selected cost ranges for mines located in Europe or the Dead Sea area are shown in table 20. Eight of these mines are located in the Federal Republic of Germany (FRG), three in France, four in Spain, one in the United Kingdom, one in Jordan, and one in Israel. The latter two utilize the resources of the Dead Sea. All of the mines were producing operations in 1984.

Table 20.—Potentially recoverable muriate per selected cost ranges for mines located in Europe or the Dead Sea area, million metric tons

Cost range, US$/mt	Quantity within range	Cumulative quantity
Less than $60	209.3	209.3
$60 to less than $80	183.7	393.0
$80 to less than $100	39.8	432.8
$100 or more	25.5	458.3
Total	458.3	NAp

NAp Not applicable.

Most of the mines located in the FRG produce additional potash products in addition to muriate, the revenues of these products were credited to the operation, but this tonnage represents only the muriate. These costs include the cost of transportation to port or market which averaged approximately $3/mt product. This table demonstrates that most of the potentially recoverable muriate is in the lower cost range.

The total muriate cost-tonnage relationships for potash mines and deposits located in the United States are shown in figure 12. Most of these are producing operations. The table shows both the relationship including the cost of transportation to market and the relationship with costs f.o.b. mill. The transportation cost is the cost to transport the product by rail to a typical market in the United States. For mines in New Mexico, a midwestern market was used, with a transportation cost of $49/mt product shipped.

At a cost less than $127/mt product (approximately the January 1984 market price of $76/mt product f.o.b. mill plus transportation costs), approximately 82 million mt product could potentially be recovered. This is close to the 84 million mt recoverable muriate of potash associated with producing mines shown in table 19. This shows that mining operations in the United States are viable at 1984 prices. At costs, including transportation, less than $100/mt, less than 18 million mt is potentially recoverable. The total muriate cost-tonnage relationship for the same mines, with the costs f.o.b. mill, illustrates the significance of transportation costs in the United States.

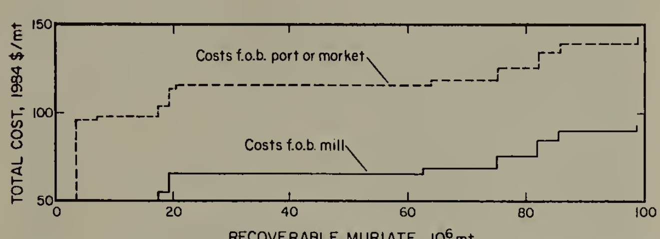

Figure 12.—Muriate potentially recoverable from mines and deposits in the United States, related to both f.o.b. mill costs and to costs including transportation.

Four other potential producers of muriate were included in this analysis. Two of these deposits are in Brazil, one in Chile, and one in the Congo. Approximately 105 million mt of muriate is potentially recoverable from these proposed mines. Most of this is associated with costs higher than those of current producers, although they would have a geographic advantage in their domestic markets.

Potassium Sulfate

The 11 properties analyzed in this study that produce or are proposed to produce potassium sulfate (K_2SO_4) are estimated to have the potential to recover 261 million mt with a grade between 50 and 54 pct K_2O, containing more than 130 million mt K_2O equivalents. Five of these properties also produce muriate of potash as a product. The muriate from these operations was included in the analysis of the potentially recoverable muriate above. Table 21 shows that producing operations account for 255 million mt, almost 98 pct of the 261 million mt potentially recoverable potassium sulfate. Analyses indicate that 252 million mt, almost 97 pct of the total, could be recovered at costs less than the January 1984 market price of $181/mt.

Table 21.—Total estimated recoverable sulfate of potash (K_2SO_4), million metric tons

	50 to 54 pct K_2O		
	United States	Italy and Federal Republic of Germany	Total
Producers	W	W	255
Nonproducers	W	W	6
Total	150	111	261

W Withheld to avoid disclosing individual property confidential data; included in total.

Potassium sulfate recoverable from four operations in the United States could potentially be 150 million mt, over 57 pct of the total. These operations could produce 142 million mt, 97 pct of the total, at costs less than the January 1984 market price. A total of 111 million mt is potentially available from five mines in Sicily and two mines in the Federal Republic of Germany. Almost 100 pct of this was associated with costs less than $181, the price in the United States as of January 1984.

Potassium-Magnesium Sulfate

Four properties in New Mexico produce or could recover potassium-magnesium sufate from langbeinite ores. Three of these operations also recover or could recover muriate of potash. The muriate from these operations was included in the analyses in the "Muriate of Potash" section.

These four properties could potentially recover 44 million mt of potassium-magnesium sulfate with a K_2O grade of near 22 pct, containing 10 million K_2O equivalents.

Potassium-magnesium sulfate potentially recoverable at delivered costs less than $115/mt would potentially be 15.4 million mt; $115/mt equals the January 1984 market price, $65/mt f.o.b. mill, plus a transportation cost of almost $50/mt.

Miscellaneous Potash Products

Mines located in the Federal Republic of Germany produce other potassium compounds that range in grade from 12 to 50 pct K_2O and sometimes contain magnesium or phosphate in addition to the potash. The revenues from these products were credited to the mines but were not included in separate cost-tonnage relationships because of their lack of homogenity and resulting wide range of market prices.

ANNUAL AVAILABILITY

Annual availability curves are disaggregations of the total resource-availability curves showing potential availability on an annual basis. Each curve represents a specific cost level. The horizontal axis represents time, either actual years for producers, or the number of years following the commencement of development for nonproducing operations. The vertical axis represents the annual production level. Increases in annual output shown on the curves represent projected expansions or new deposits which come on line; decreases represent the depletion of the demonstrated resources of some deposits, which could be offset by new discoveries or new technologies.

Muriate of Potash

The annual availability curves for producing muriate operations in market economy countries are shown in figure 13. Costs include the cost of transportation to port or domestic market. These curves increase during the 1980's, generally maintain their level until 1995, then begin to decline. An estimated 20 million mt of muriate was produced in market economy countries during 1983. Demand for muriate in market economy countries has been estimated to be 36 million mt in 1990 and 47 million mt in 2000. Estimates of demand are based on Bureau of Mines demand forecasts (*3*). The curve representing the tonnage that could be recovered at costs less than $130/mt shows that 25 million mt of muriate of potash could have been produced during 1984, it increases to the 30-million-mt level in 1992 and declines to just over 25 million mt in 2000. The curve representing the tonnage that could be recovered at costs less than $110 shows that over 22 million mt could have been produced during 1984, it increases to near the 28-million-mt level in 1992 and declines to just over 23 million mt in 2000. The curve representing the tonnage that could be recovered at costs less than $80 shows that over 14 million mt could have been potentially produced during 1984, it increases to over 18 million mt for the period from 1990 to 1995, and declines to over 16 million mt in 2000. These curves demonstrate that the annual tonnage of recoverable muriate associated with costs less than $110/mt at producing mines is more than current consumption but not sufficient to meet projected demand in 1990 and 2000. Even the tonnage associated with costs less than $130/mt is not sufficient to meet projected demand in 1990 and 2000. The curves for producers located in specific geographic areas, such as Canada or the United States, shown later in this section, illustrate the situation in more detail and demonstrate the importance of Canadian annual production capacity.

The annual availability curves for nonproducing muriate operations in market economy countries are shown in figure 14. These curves increase until the seventh year after the commencement of development then generally level off for the rest of the curve. The curve representing the tonnage that could be recovered at costs less than $250/mt increases to 18 million mt in the seventh year (N+7) after the commencement of development then levels off for the remainder of the curve. At costs less than $200/mt, tonnage would increase to near 8 million mt in the seventh year, then level off, while at $110, tonnage would approach 3 million mt in the fifth year before leveling off. This figure demonstrates that the recovery of potash from operations not now in production would require much higher prices as an incentive to initiate production, and even with much higher prices, the recoverable muriate potentially available from both producing and nonproducing operations would not quite meet projected demand.

The annual availability curves for producing potash mines in Canada are shown in figure 15. The costs in this analysis include the cost of transportation to port or domestic market, which averages approximately $32/mt product. Both curves shown on this figure increase to their maximum level of production and can continue to produce at this level past 2000. This is because Canadian mines have vast resources and long lives. The increases in annual production shown by these curves reflect projected expansions in output that were built into the analyses of this report.

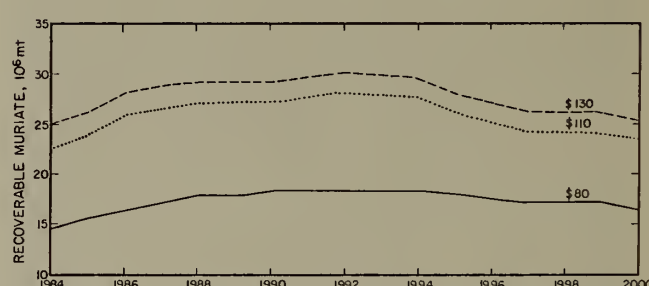

Figure 13.—Potential annual production of muriate from producing mines in market economy countries at various cost levels.

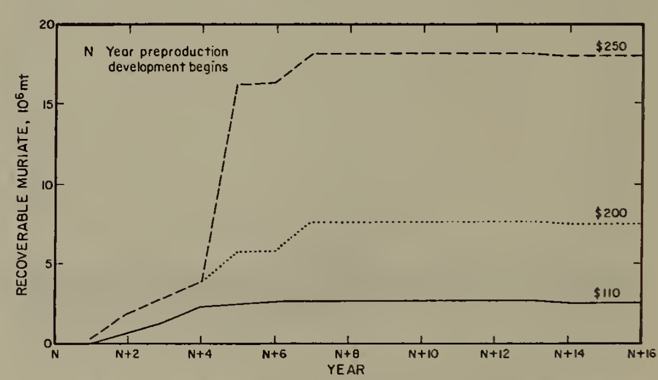

Figure 14.—Potential annual production of muriate from nonproducing mines in market economy countries at various cost levels.

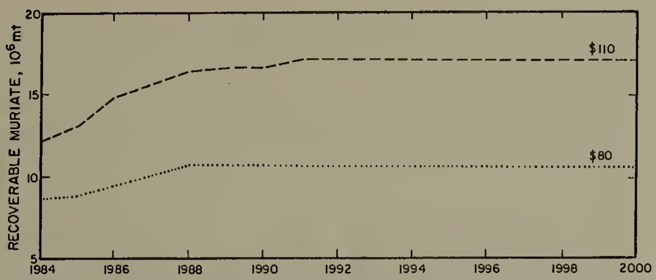

Figure 15.—Potential annual production of muriate from producing mines in Canada at various cost levels.

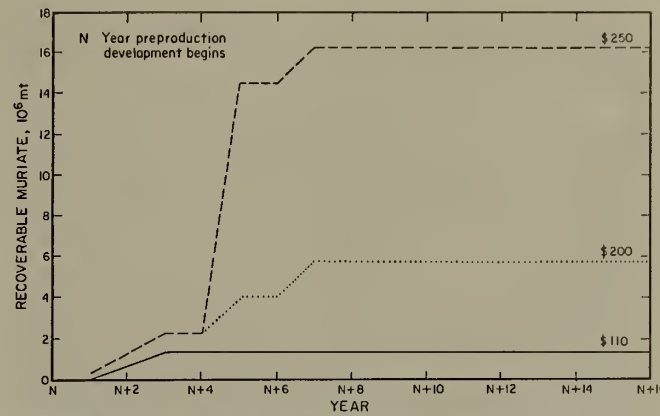

Figure 16.—Potential annual production of muriate from nonproducing mines in Canada at various cost levels.

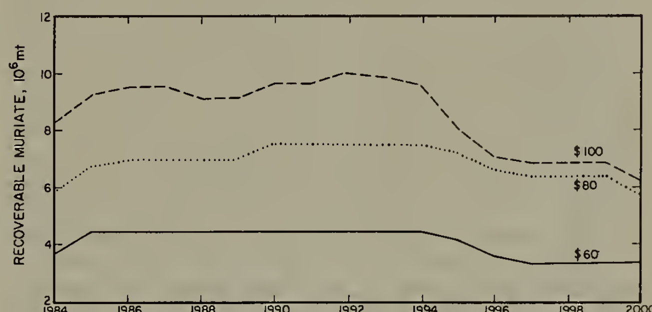

Figure 17.—Potential annual production of muriate from producing mines in Europe and in the Dead Sea area at various cost levels.

The curve representing the tonnage that could be recovered at costs less than \$110/mt, which is approximately the 1984 Canadian f.o.b. price plus an average transportation cost of \$32/mt, increases from just over 12 million mt in 1984 to just over 17 million mt in 1991 and holds that level of production through 2000. At a cost of under \$80/mt, the muriate tonnage that could be recovered in 1984 is almost 9 million mt and by 1990 it rises to near 11 million mt where it remains through 2000. Canada produced 10 million mt of muriate in 1983 and exported more than 6 million mt to the United States.

In recent years Canada has exported nearly two-thirds of its production to the United States, and imports to the United States from Canada have been two-thirds of consumption. The U.S. demand for muriate in 1990 could be about 13 million mt, in 2000, 16 million mt. Two-thirds of this demand could be supplied by two-thirds of Canadian production at costs less than the January 1984 market price plus transportation, \$110/mt. The tonnage that could be recovered at under \$80/mt is almost sufficient to supply future demand from the United States. At costs less than \$110/mt, Canada could produce enough muriate to satisfy all of the projected demand in the United States.

The annual availability curves for nonproducing potash mines in Canada are shown in figure 16. The costs of production and transportation for most of these properties is significantly above 1984 market prices plus \$29/mt for transportation. The price of potash would have to increase substantially for most of these proposed operations to generate the revenues necessary to cover their costs. The annual tonnage that could potentially be recovered at costs less than \$250/mt is 16 million mt. The annual tonnage that could potentially be recovered at costs less than \$200/mt is near 6 million mt. The annual tonnage that could potentially be recovered at costs less than \$100/mt is over 1 million mt from the third year through 2000.

The annual muriate availability curves for mines in Europe and near the Dead Sea area are shown in figure 17. All these mines were in production at the time of this analysis. Costs include transportation to port or market which averages less than \$5/mt product. Transportation costs are less than those for Canada or the United States because there is less distance to the port or market in these countries. An ocean freight rate has to be added to the costs on the curves to compare the costs to prices in the United States. A typical ocean freight from a Mediterranean port to a North American port is \$14.25 (*19*). The January 1984 price in the United States was \$76/mt.

All three curves in the figure show a projected increase in production in 1985, then are relatively constant until 1995 when they start to decline. The curve representing the tonnage available at costs less than \$100/mt projects that annual production could potentially be over 8 million mt in 1984, increasing to more than 9 million mt from 1985 through 1994. Actual 1983 production was estimated to be less than 7 million mt.

The curve representing the tonnage potentially available at costs of less than \$80/mt is under 6 million mt in 1984, almost 7 million mt in 1986, increasing slightly to more than 7 million mt in 1990 and staying at that level until 1995 when it begins to decline. At costs less than \$60/mt less than 4 million mt is available in 1984, increasing to over 4 million mt in 1985 and staying constant until it begins to decline in 1995. The declines are a result of the static nature of the resources included in this analysis. The demand for these resources will continue because of their low costs, but if new low-cost resources are not found, their output will decline.

Annual muriate availability curves for mines producing at the time of this analysis in the United States are shown in figure 18. The curve representing the tonnage available at costs less than \$127/mt, the January 1984 price f.o.b. mill plus an average transportation cost of about \$49/mt product, shows 2.8 million mt potentially recoverable from 1984 to 1988 when it begins to decline. It would be just under 2.0 million mt from 1990 to 1996; after 1997 it would be near 1.2 million mt. The tonnage potentially recoverable annually at costs less than \$100/mt is almost 1.5 million mt from 1984 until 1989, it then declines to under 1 million mt until 1996 after which it

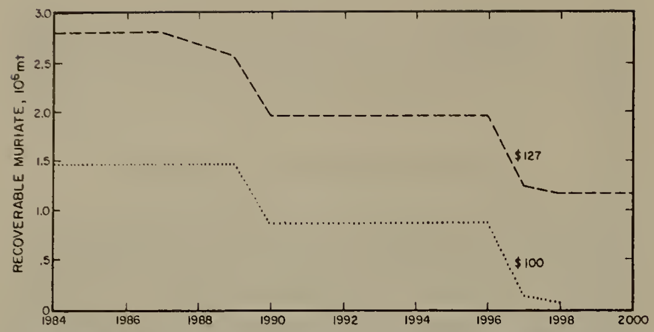

Figure 18.—Potential annual production of muriate from producing mines in the United States at various cost levels.

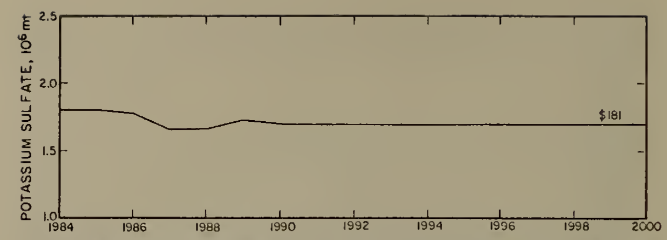

Figure 19.—Potential annual production of potassium sulfate from producing mines in market economy countries.

declines further. These declines are based on the assumption that all mines are operating at full capacity. If mines operate below full capacity, then the declines are delayed.

Production of muriate was near 20 pct of apparent consumption of all potash in the United States in terms of contained K_2O in 1983, down from near 29 pct in 1982. Demand for potash is projected to increase 40 pct over apparent consumption in 1983 by 1990 and 75 pct by 2000. The annual tonnage of muriate potentially recoverable at costs less than $127/mt could supply 30 pct of the 1984 demand, 15 pct of the 1990 demand, and less than 8 pct of the demand in 2000. The tonnage potentially recoverable annually at costs less than $100 could supply 16 pct of 1984 demand and less than 8 pct of the demand in 1990. These data show that resources associated with producing mines are not sufficient to maintain the 1984 share of demand in the United States in the future.

Annual production of muriate from the three nonproducing deposits in the United States could potentially be 850,000 mt, with average costs about over $180/mt, with costs less than $141/mt, they could produce 750,000 mt. This is not enough to replace the resources at the producing mines when they are depleted. This analysis demonstrates that unless new low-cost resources are discovered in the United States, the decline in the ratio of domestic production to domestic consumption will continue. This decline should not be a problem for consumers in the United States because Canadian resources have the potential to supply projected demand in the United States.

Potassium Sulfate

The annual availability curve for world potassium sulfate producers is illustrated in figure 19. It shows that at costs including transportation of less than $181/mt (the 1984 price f.o.b. mill in the United States was $181/mt), 1.8 million mt could be produced in 1984 and 1985. This is the amount produced in 1983. Production in 1986 could be just below that number, and from 1987 through 2000 production could remain fairly constant at 1.7 million mt.

Annual production from the three nonproducing operations could be approximately 300,000 mt with average costs more than double the January 1984 market price. These potential capacities are not sufficient to meet the projected world demand for potassium sulfate in 1990 and 2000 of over 2 million mt and 3 million mt, respectively. To supply the projected demand, annual capacity at existing deposits will have to be expanded.

Annual production of potassium sulfate from producing mines in Italy could be above 500,000 mt from 1984 to 1986, then remain above 400,000 through 2000. Actual production in 1982 was approximately 240,000 mt. All Italian producers have costs below $181/mt.

Annual production of potassium sulfate from producing mines in the United States is projected to remain above 300,000 mt from 1984 through 2000. Production in 1983 was more than 300,000 mt. The average cost for producers in the United States is significantly below $181/mt.

Potassium-Magnesium Sulfate

Production of potassium-magnesium sulfate and other minor potassium salts was under 700,000 mt in 1982. This was near the tonnage potentially recoverable annually from producing mines in 1984 and through 2000. However, the costs associated with this tonnage are above the January 1984 market price of $65/mt. Annual availability of potassium-magnesium sulfate from nonproducers is projected to be more than 1 million mt from the 4th year after the beginning of development until the 14th year. Together, producing and nonproducing operations could potentially recover annually almost 2 million mt. The average costs for the tonnage recoverable from both producers and nonproducers is approximately $139/mt product.

CONCLUSIONS

Potassium is an important component of fertilizers required to maintain the yields of the world agriculture industry. This study evaluated 68 mines and deposits in 12 market economy countries. Three additional deposits were not included in the detailed analysis; one contained no demonstrated resources and the other two produced potash only as a byproduct. Deposits were selected in order to include demonstrated resources associated with at least 85 pct of the production of potash in significant market economy countries, and to include the demonstrated resources associated with nonproducing deposits that were equal to those of producing mines and that could be mined and processed with current technology.

Approximately 11.7 billion mt K_2O is contained in the mines and deposits evaluated in this study. These resources include 190 million mt in the United States (not including

Searles Lake or the Salton Sea, which contain an additional 162 million mt), 9.63 billion mt in Canada, approximately 430 million mt in Western Europe (France, Federal Republic of Germany, Italy, Spain, and the United Kingdom), 1.24 billion mt in the Middle East (Israel and Jordan), and over 220 million mt in other countries (Brazil, Chile, and the Congo).

Five and one-half billion metric tons of muriate of potash, containing 3.4 billion mt K_2O equivalents; 261 million mt of potassium sulfate, containing more than 130 million mt K_2O equivalents; and 44 million mt of potassium-magnesium sulfate, containing 10 million mt K_2O equivalents, are potentially recoverable from the 68 mines and deposits analyzed in this study. Seventy-seven percent of the revenues from the operations included in this study would be from muriate, 16 pct from potassium sulfate, and 7 pct from other products. More than 88 pct of the potentially recoverable muriate is in Canada; over 57 pct of the sulfate is in the United States, with the remainder in Italy and the Federal Republic of Germany.

Estimates based on this analysis show that for all deposits included in this study, almost one-half of the total muriate of potash product, more than 3 billion mt, could be recovered at costs (including transportation) of less than \$110/mt. At this price, 22 million mt could be potentially recovered annually from producing operations in 1984 (20 million mt was produced in 1983), increasing to 28 million mt after planned expansions. However, analysis indicates that muriate prices exceeding \$130/mt will be required to meet projected demand in 1990 or 2000.

Canada was the largest market economy potash producer in 1983. Over 82 pct of the in situ K_2O equivalents associated with deposits included in this study are located in Canada. Muriate product potentially recoverable from Canadian deposits totals 4.8 billion mt, 2.6 billion mt of this could be recovered at costs less than \$110/mt, the January 1984 price f.o.b. mill plus an average transportation cost to the point of export. At costs including transportation of \$80, 40 pct of the 2.6 billion could be recovered. At costs less than \$110/mt, 12 million mt could be potentially recovered annually from producing operations in 1984, increasing to 17 million mt after projected expansions. At costs less than \$80, 9 million mt is potentially recoverable in 1984, increasing to near 11 million mt by 1990 and staying there through 2000. Costs associated with nonproducing mines in Canada are substantially higher than those for producers.

More than 6 million mt of Canada's 1983 production of 10 million mt was exported to the United States. It made up two-thirds of the potash consumed in the United States. The annual muriate recoverable at costs less than \$110/mt is sufficient to supply two-thirds of U.S. consumption through 2000.

Almost 460 million mt of muriate of potash could potentially be recovered from operations in Europe and near the Dead Sea. At a price of \$80/mt, including an average transportation cost of less than \$5/mt, more than 85 pct, 393 million mt, could potentially be recovered. At this price, almost 6 million mt (which is about equal to 1983 production), could be potentially recovered annually from producing operations in 1984, increasing to almost 7 million mt after planned expansions. All operations in this area that were included in the analysis were producing.

More than 100 million mt of muriate of potash could potentially be recovered from operations in the United States. At \$127/mt, the January 1984 price (including an average transportation cost of almost \$50/mt), 82 million mt could potentially be recovered. At costs less than \$100/mt, 18 million mt could be recovered. The annual tonnage of muriate that could be recovered at costs less than \$127/mt is 2.8 million mt from 1984 to 1989, after which it begins to decline. The annual tonnage that could be recovered at costs less than \$100/mt is almost 1.5 million mt from 1984 to 1989 then begins to decline.

The percent of consumption supplied by domestic production of muriate in the United States has been declining, in 1983 it was about 20 pct, down from 29 pct in 1982. The annual tonnage potentially recoverable at costs less than \$127/mt could supply 30 pct of the 1984 U.S. demand, 15 pct of the projected 1990 demand, and less than 8 pct of the projected demand for 2000. The annual tonnage potentially recoverable at costs of \$100/mt could only supply 16 pct of the 1984 demand and 8 pct of the 1990 demand. These declines will have a significant impact on producers, but it is not necessarily a problem for consumers in the United States because Canadian resources have the potential to meet the projected increases in demand in the United States. Resources associated with the three nonproducing U.S. deposits included in this analysis are not large.

Ninety-seven percent of the potassium sulfate, 252 million mt, could be recovered at costs (including transportation) of less than \$181/mt, the January 1984 price. At this price, 1.8 million mt could be potentially recovered annually from producing operations in 1984. Potential annual recovery of sulfate declines gradually after 1984. With the capacity from nonproducing operations, it is not sufficient to meet projected demand. To meet future annual demand, either new resources will have to be discovered or annual capacity associated with resources at producing operations with large resources will have to be expanded.

Almost 150 million mt of potassium sulfate could potentially be recovered from operations in the United States. Annually, more than 300,000 mt could be potentially recovered from producing operations in the United States, which is equivalent to the 1983 production. This tonnage is sufficent to meet the projected demand for potassium sulfate in the United States for 1990 and 2000 of 240,000 mt and 300,000 mt, respectively. More sulfate capacity will have to be developed or the United States will consume all of its production instead of exporting it as it did in 1983.

Canadian potash producers have large resources capable of meeting demand well into the future. Potash mining in the United States can continue, but at declining production rates. Overseas production from market economy countries can continue into the next century at near current production levels. Producing mines in Canada have large resources and can maintain production many years past 2000.

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APPENDIX.—GEOLOGY OF POTASH DEPOSITS EVALUATED

Following is a discussion of the deposits that were evaluated as a part of this study. For every country, a brief geologic discussion is included. However, in certain countries such as Canada where many mines are exploiting one geologic area, the geology and resources of that region are discussed.

UNITED STATES

New Mexico

Potash deposits of the Permian Basin in New Mexico have been the major source of production in the United States since the mid-1930's. Sylvinite and langbeinite are both mined. Sylvinite is the primary ore, with an average grade near 18 pct K_2O. The exploitable potash deposits are located in the Carlsbad district, in southeastern New Mexico, on the edge of the Delaware Basin, a sub-basin of the Permian Basin. The evaporites of the Delaware Basin are part of the extensive evaporites of the Ochoa Series, which covers an area roughly 420 by 350 km. The Ochoa Series contains three evaporite formations, the Castille Formation, which was deposited first, next is the Salado Formation, and on top of that was deposited the Rustler Formation. Together they are 1,300 m thick. The Salado Formation contains the McNutt potash zone. Most of the potash is in the form of polyhalite, with sylvite restricted to a small area. The McNutt potash zone ranges from 50 to 140 m thick in the Carlsbad district. It contains 11 ore zones, 5 of which have been exploited.

Utah

Great Basin

The Great Basin includes the areas of the Great Salt Lake and the Great Salt Lake Desert. Lake Bonneville is the name of the last of a succession of Pleistocene lakes which, at its maximum extent, covered 51,800 km² and at its highest was about 300 m above the present level of its largest remnant, the Great Salt Lake. The Great Salt Lake lies in the eastern part of the area that was covered by Lake Bonneville. In 1957 a railroad causeway was constructed across the lake, dividing it into a north arm and a south arm. As a result the south arm receives most of the fresh water; and the north arm has become denser and more saline. Potash recovery from the north arm began in the mid-1960's. The percentage of mineral ions in the north arm, reported in 1979, is shown in table A-1. High levels of precipitation in the early 1980's have caused the lake level to rise, making the lake less saline. Because of the high level of the lake, the causeway was breached in August 1984, making the north arm even less saline and resulting in a larger volume of brine needed to recover a given quantity of product.

Table A-1.—Dissolved solids in the Great Salt Lake, 1979 (*2*), percent

Na	8.15	Cl	14.75
K	.58	SO_4	1.78
Mg	.92	CO_3	.07
Ca	.10	SiO_4	([1])
Fe	([1])	NO_3	.06

[1]Less than 0.005 pct.

The Bonneville Salt Flats are on the western edge of the Great Salt Lake Desert. They were formed from the evaportion of an intermittent playa lake separated from the Great Salt Lake when the lake level dropped below 1,200 m above sea level. The salt crust covers an area 380 km² and is 1.5 m thick at its center. Below the salt crust are lacustrine and fluvial sediments, the upper 6 m of which make up an aquifer in which potash-rich brines circulate. The source of the potash in the brines is from incoming surface water or from dissolved solids derived from the host sediments. Table A-2 shows a chemical analysis of the soluble portion of the sediments reported in 1979 (*2*).[1] The salt crust also contains brine but this brine is not particularly potash rich. The first attempt to recover potash in 1919 was not successful. The current operation started in 1937.

Table A-2.—Soluble portion of Bonneville Salt Flats sediments, 1979 (*2*), percent

K	0.07	Mg	0.10
Na	38.85	SO_4	2.88
Ca	1.20	Cl	58.98

Paradox Basin

Potash minerals occur in the evaporites of the Paradox Formation, a member of the Hermosa Group, in the Paradox Basin near Moab, UT. The Paradox Basin is a structural downwarp that has been extensively modified by uplifts and upwarping. Eleven evaporite layers contain potentially recoverable potash, several with K_2O content exceeding 30 pct. The beds are extensively folded. At the Cane Creek Mine, the potash ranges near 1,000 m in depth, the sylvinite horizon is 3.4 m thick and contains 25 to 30 pct K_2O. The Cane Creek Mine began production as an underground mine in 1964, it was converted to a solution mine between 1970 and 1972, in 1972 production commenced at the solution operation (*2*).

California

Searles Lake

Searles Valley area in California, a part of the sonoran desert, was the site of several large lakes during the Pleistocene era. Searles Lake is the nearly desiccated remnant of a much larger lake which once formed part of the Owens River drainage system. The evaporite deposit of Searles Lake consists of alternating mud beds and brine-saturated salt beds (*20*). Brine from the Searles Lake is processed at three plants to produce soda ash (Na_2CO_3), borax ($Na_2B_4O_7$), potash (KCl), and salt cake (Na_2SO_4). A typical Searles Lake brine analysis shows 4.3 pct K_2O. Potash is produced only at the one plant, the Trona plant. The deposit contains about 61 million mt of K_2O. Potash is only a byproduct, and as such the operation was not included in the primary potash availability analysis of this study. The

[1]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

resource is included in the resource discussion and production is included as part of total production in the United States.

Salton Trough

The Salton Trough in southern California is a 320-km-long depression. Within the Salton Trough, on the southeast shore of the Salton Sea is the Salton Sea geothermal system composed of Pleocene and Quaternary sediments of the Colorado River Delta *(21-22)*. There is little evidence of folding or faulting. The brine was originally Colorado River water that has been trapped in deltic sediments and became saline through countless cycles of evaporation *(22)*.

The Salton Sea known geothermal resource area in California was not included in the availability analysis because, as in the Searles Lake operations, potash would only be a byproduct. As of 1980, there were no leases in this area. The resource in situ is 6,273 million mt of brine with an average grade of 1.6 pct K_2O giving in situ K_2O of 100.8 million t.

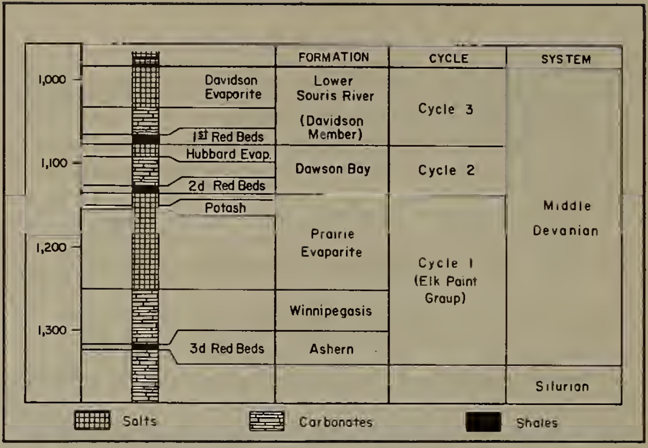

Figure A-1.—Columnar section showing Middle Devonian evaporite cycles. (Courtesy Saskatchewan Energy and Mines)

CANADA

Saskatchewan

Canada has 81 pct of the potash resources of market economy countries included in this study. Although some potash exists on the east coast of New Brunswick, over 95 pct of the resource in Canada is located in the southeastern corner of the Province of Saskatchewan. Demonstrated in situ resources in Canada total 9.63 billion mt K_2O.

Potash was unintentionally discovered in Saskatchewan in 1942 by oil companies that were conducting exploration in the area. It was another 10 yr before there was any exploration to determine the potential of the potash resource. Once the potential was realized, another 10 yr passed before the first mine opened; the delay being attributed to shaft sinking problems. In 1983, 10 mines, 9 using conventional room and pillar and 1 using solution methods, produced a total of over 6 million mt K_2O.

Potash in Saskatchewan was deposited 400 million yr ago during the Devonian Period in the Prairie Evaporite Formation of the Elk Point Basin. During Middle Devonian times, three evaporitic cycles occurred (fig. A-1). The first cycle of deposition, sometimes known as the Elk Point Group, consists of the Ashern Formation Shales, Winnepegosis carbonates, and Prairie Evaporite Formation. The Prairie Evaporite Formation contains the valued potash beds. The second cycle is solely composed of the Dawson Bay Formation and consists mostly of halite and the clay insolubles of the second red beds. The third and final cycle denoted by the lower Souris River (Davidson Member) is also a halite formation separated from the Dawson Bay Formation by the First Red Beds.

The Prairie Evaporite Formation is generally horizontal with a slight dip to the southwest, the top of the formation is encountered at 400 m below the surface north of the potash areas, and gradually dips to 3,000 m below the surface in Montana and North Dakota. The upper part of the Prairie Evaporite Formation contains the four groups of potash-bearing beds. Three of these groups, the Patience Lake Member, the Bell Plaine Member, and the Esterhazy Member, are currently exploited for potash. The fourth group, the White Bear Member, is small and not continuous, and is not currently exploited (fig. A-2).

Of the four members, the Patience Lake Member is stratigraphically the shallowest. It extends east from the town of Unity, where its areal extent is the greatest, through Saskatoon where its thickness is at its maximum, 21 m, and to Yorkton where it thins out. The Patience Lake Member is unique in the fact that it has two separate ore zones. The upper zone has four to seven individual beds with average thicknesses of about 3 m, and average grade of about 25 pct K_2O. The Vade, Cory, Patience Lake, Allan, and Central Canadian Potash Mines produce ore from this zone. The lower zone consists of five individual beds with average thicknesses of 6 m. The average grade for these beds is 20 pct K_2O; however, the upper beds contain a slightly higher K_2O content. The Lanigan and Allan Mines extract ore from the lower zone.

The Belle Plaine Member underlies the Patience Lake Member and is separated by a 3– to 12–m zone of halite. Although the Belle Plaine is approximately equal to the Patience Lake Member in area, it is more consolidated when compared with the stringiness of the Patience Lake Member, and is found south of the Patience Lake Member.

The White Bear Member underlies the Belle Plaine Member. It is a very small member located in the southeast corner of Saskatchewan and into Manitoba. The average thickness is about 7.5 m. Since the bulk of this member is located below the 1,000-m conventional mining limit, the White Bear Member is not presently considered for mining. However, a potential for solution mining exists for the future.

The fourth and stratigraphically lowest member is the Esterhazy. The Esterhazy Member is found southeast of the Belle Plaine Member. It occurs in the southeast corner of Saskatchewan and has projections into Manitoba, Montana, and North Dakota. The member is about 2.4 m thick with an average K_2O content of about 25 pct. The Esterhazy Member is exploited exclusively in the southeast part of

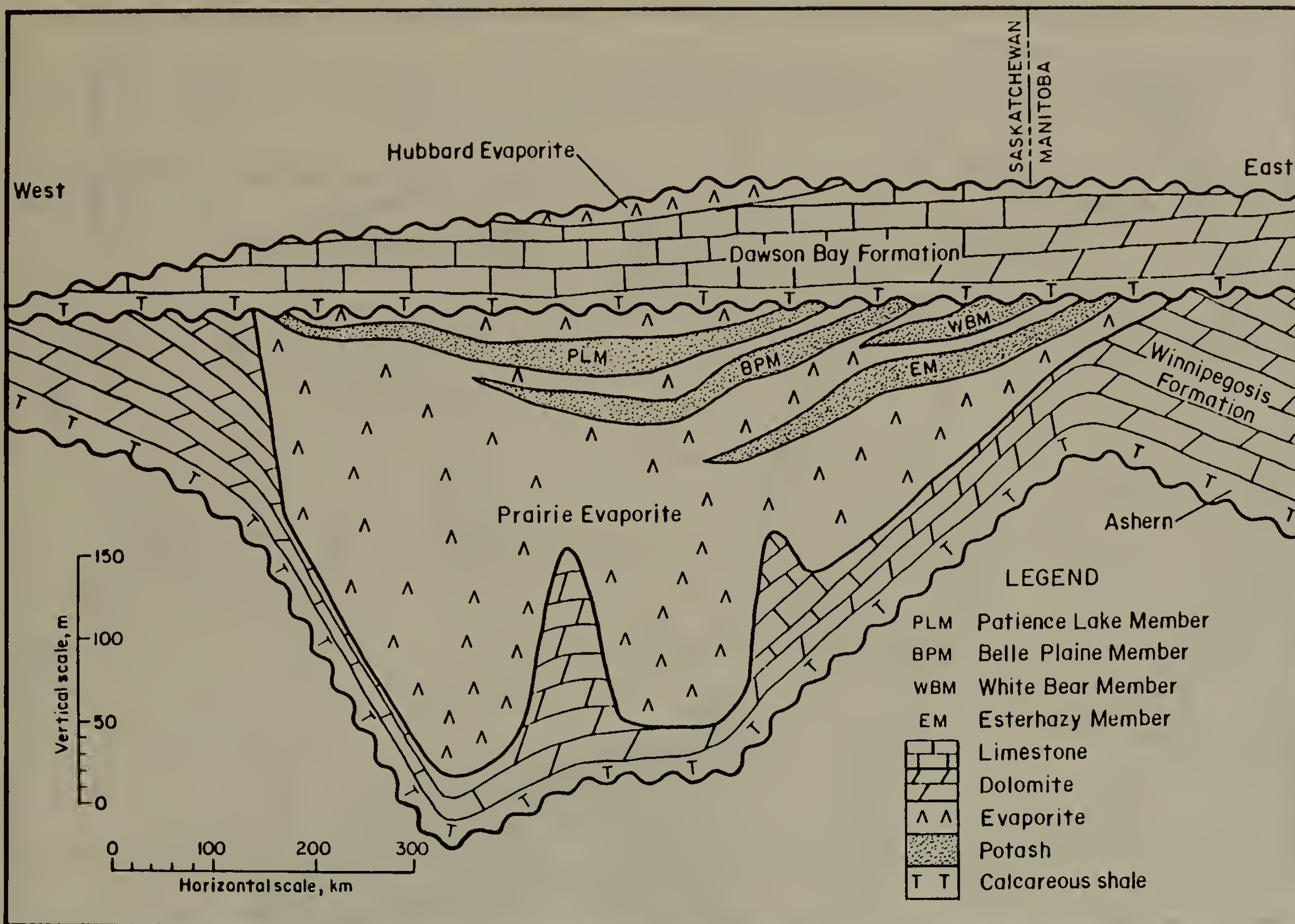

Figure A-2.—Diagrammatic cross section through the Prairie Evaporite Formation in Saskatchewan and Manitoba. (Courtesy Saskatchewan Energy and Mines)

Saskatchewan, by the Esterhazy K-1 and K-2 Mines, the Rocanville Mine, and by two proposed mines, Bredenbury in Saskatchewan and McCauley in Manitoba. Figure A-3 shows the areal extent of the Prairie Evaporite Formation; figure A-4 shows the location of operating potash mines.

Mining potash in Saskatchewan, as described in the "Mining" section of this report, is a relatively simple operation. However, some problems had to be overcome before profitable mining could be achieved. New shaft sinking technology had to be developed in order to go through a formation known as the Swan River or Blairmore. The Blairmore is Lower Cretaceous in age and is a part of the Mannville Group. It consists of very loose sands with clays and shales. But what makes it a mining problem is that it is a high-pressure, brine-bearing formation, the brine in some areas being under pressure of up to 475 psi. After about 10 yr of research, a method was developed that enabled miners to freeze the water in the area around the location of the shaft and install a sleeve to keep out the water. This technology assisted in the development of these potash resources and high-capacity mining operations were soon in progress.

Once mining began, the problem of salt horses was encountered. Salt horses are basically a pocket of waste rock, usually halite, found in the potash bed. A salt horse is a problem because it not only interrupts the continuity of the deposit but also poses a roof stability problem in that area of the mine.

Three types of salt horses have been defined in the region. One type of salt horse is the result of stream channels cut into the salt bed. The potassium, which is very soluble, was removed and replaced with some gangue mineral. Another type is the result of a lowered water table. As the water table decreased, potassium was leached out of the ore body. In some cases, the thickness of the ore even decreased, the leached potassium being replaced by sodium chloride.

The third and possibly the worst type of salt horse is caused by voids created underneath the ore body. High pressure from the overlying rock then causes the upper beds to collapse. Some operations have encountered shale and limestone breccia cemented with halite. This brecciated material, when mined, poses a roof stability problem, resulting in special roof support requirements.

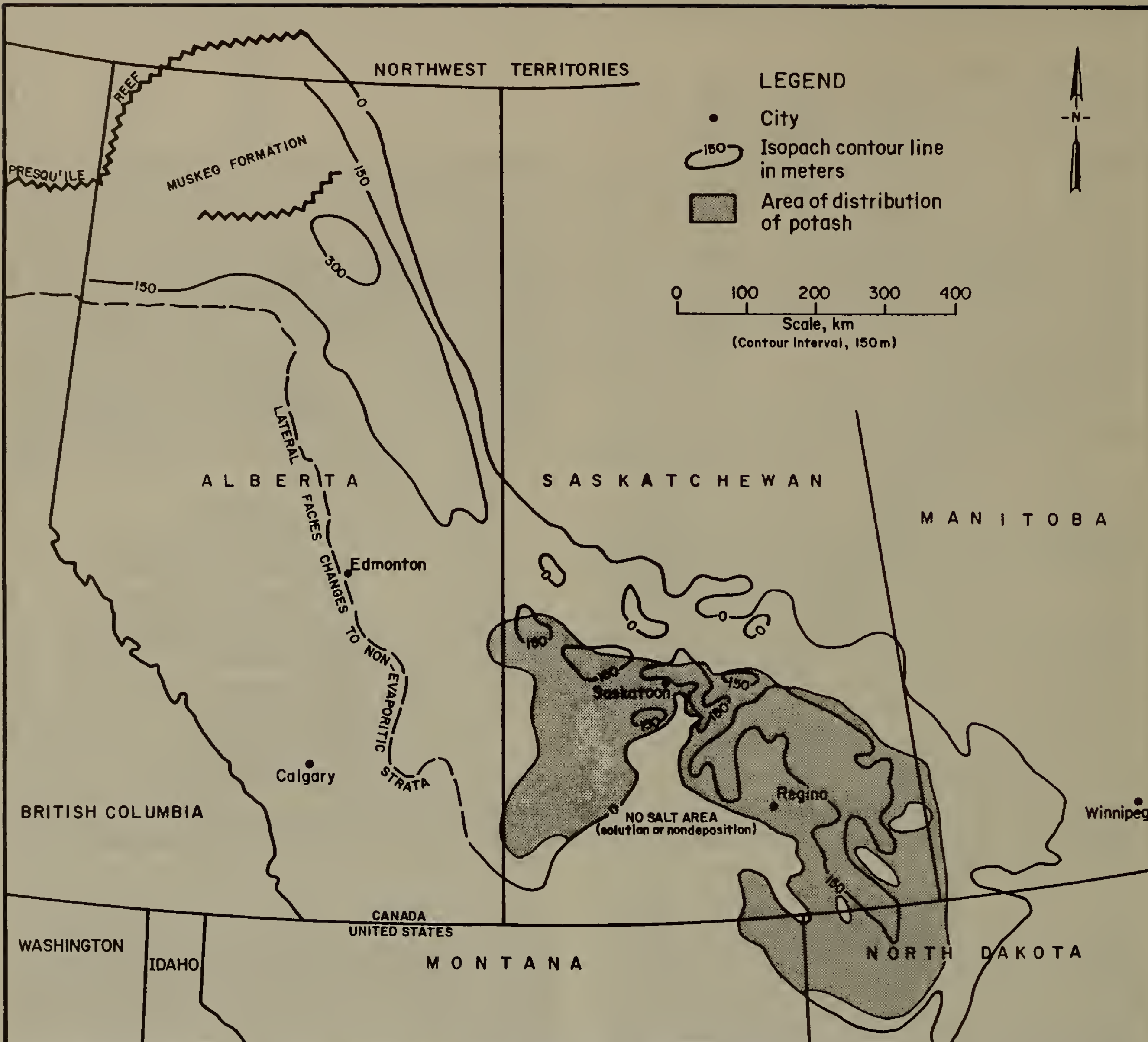

Figure A-3.—Isopach map of the Prairie Evaporite Formation in the Elk Point Basin. (Courtesy Saskatchewan Energy and Mines)

New Brunswick Potash

In an exploratory drilling program conducted by the New Brunswick Government, potash was discovered in three salt domes, all of which are in the Windsor Group of the Moncton Basin. Two of the domes, one near Salt Springs and another near Sussex, each indicated a single bed containing a high grade of sylvite. Potash Co. of America developed a mine near Sussex that started up in 1983. International Minerals and Chemicals (IMC) originally explored the Salt Springs area, but in 1984 Denison Potash Mines was developing a mine there. The third salt dome, located by Millstream, was being explored during 1984 by BP Canada.

CHILE

Within the Salar de Atacama desert in northern Chile is a dry-lake-bed brine deposit thought to be of adequate size and grade to support commercial exploitation. Other areas in the region, such as Salar el Miraje, approximately 175 km northwest of the Salar de Atacama and Salar de Bello Vista, approximately 200 km north of Salar el Miraje, show some promise of containing marketable potash. However, none are as promising as the Salar de Atacama.

The Salar de Atacama is a closed basin system that receives runoff from a small area of the Andes and from secondary ranges surrounding the basin, as well as from

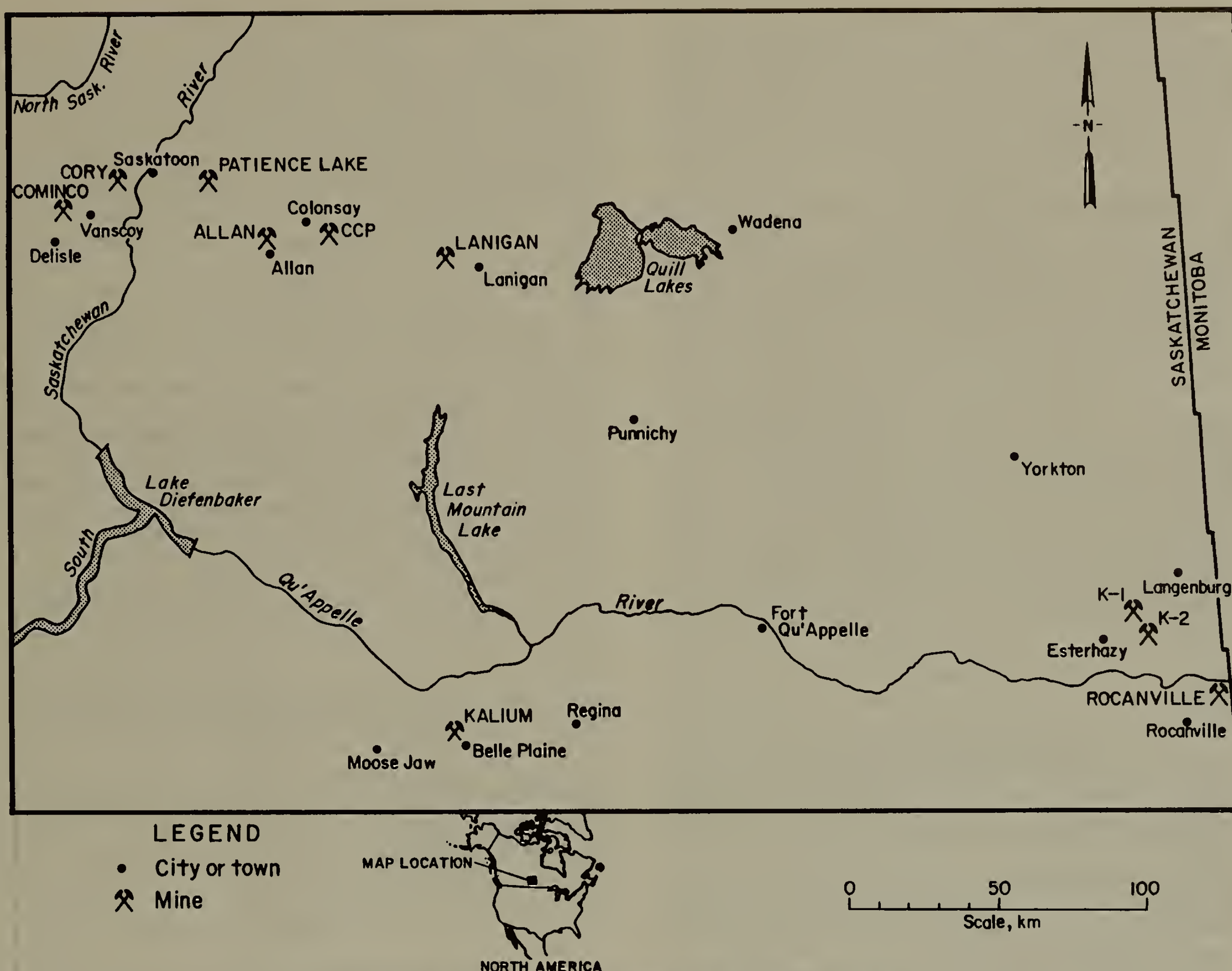

Figure A-4.—Location map, potash mines in Saskatchewan.

springs. The depression, which contains the Salar, is partially filled with clastic sediments and evaporites. The origin of this deposit is attributed to the capillary concentration of highly soluble salts. The water-saturated basins receive the erosion products of the surrounding mountains, which contain high amounts of sodium and potassium. The solution evaporates causing the minerals to precipitate. The more soluble salts are being carried farther upwards through the soil before precipitating. The potential potash minerals for exploitation are contained in these circulating brines, which occur approximately 30 m below the surface.

The Salar extends over an area of 3,000 km². The central nucleus of the Salar is a massive halite evaporite body extending over 1,400 km² and to a depth of 30 m and containing in its interstices a brine particularly rich in potassium and lithium values. Corporación de Fomento de la Producción (CORFO) is currently contracting for engineering design services to proceed with development of a facility to recover 500,000 mt/yr KCl product and 150,000 mt/yr K_2SO_4 product.

BRAZIL

There were two distinct potash-bearing deposits in Brazil that were being developed in 1982. They are the Taquari-Vassouras prospect in the Sergipe Basin and the Fazendinha claim in the Amazon Basin.

The Sergipe Basin is a long narrow strip of coastline and continental shelf. It is different from most other potash deposits in that it contains abundant amounts of tachyhydrite ($2MgCl_2CaCl_212H_2O$), a mineral that only forms from brines that are rich in calcium. These features are also apparent in evaporites of the Congo and Gabon Basins in western Africa. It is believed that the initial splitting of South America from Africa during Jurassic times resulted in a structural situation, similar to that of the Red Sea splitting during the Miocene, in which evaporites were able to form. During the separation of the two continents, calcium-rich brines were introduced from the ocean floor, which is now the Atlantic Ocean, and made the formation of tachyhydrite possible.

Tachyhydrite is highly hygroscopic and has low mechanical strength. Contact with the atmosphere during mining must be avoided to prevent swelling of the tachyhydrite layers. Studies to assess the safe mining distance from this bed are currently being conducted.

The Sergipe Basin is 150 km long by 30 km wide. There are two sylvinite beds separated by a layer of halite within a Cretaceous Age sedimentary formation in the Sergipe Basin. Sergipe sylvinite is abnormally low in bromine and high in rubidium compared with primary sylvinite and is thought to have been derived by leaching from carnellite. It is uncertain whether the lower sylvinite bed will be mined or not because of its proximity to tachyhydrite. Both sylvinite layers have a minable thickness ranging from 2 to 10 m. The depth to the top layer is 460 m.

The Permian evaporites of the Amazon Basin represent a regressive evaporite sequence. Underlying the thick layering of anhydrite and rock salt is upper carboniferous marine limestone and sandstones; above is Upper Permian to Lower Triassic red shales deposited in a continental-lagostrine environment. A retreating sea proceeded from open marine conditions ultimately to the formation of lagoonal conditions, then isolated lakes. The formation of these lakes finally led to brine of sufficiently high concentration to precipitate high-bromine halite, then KCl as sylvite.

CONGO

A series of connected sedimentary basins stretches across the west African coast from Angola to Gabon. The basin zone is about 5 to 20 km wide. The two northern basins, the Gabon and the Congo, are related and probably have the same origin as the Sergipe evaporite basin in Brazil.

In terms of potash resources, the Congo Basin is of more importance than the Gabon Basin because of the well-developed salt strata that the Congo Basin contains. Ten evaporite deposition cycles exist in the Congo Basin and are numbered I to X, starting with the deepest cycle. Each cycle represents a period of deposition and evaporation that occurred during Cretaceous times as the area alternated between marine and continental environments. The potash-bearing beds occur above the halite and the entire sequence is overlain with bisschofite and tachyhydrite.

Sylvite and sylvinite ores were formed by the leaching of magnesium chloride from carnallite and are, therefore, irregular in occurrence. Deposits tend to be tabular, and extensive and can contain carnallite lenses.

The Holle (St. Paul) potash deposit of the Congo Basin contains some of the world's highest grade potash ore, part averaged 35 pct K_2O. However, when it was mined between 1969 and 1977 it showed a loss because of the carnallite pockets that were encountered. Results of a feasibility study that was conducted suggested that profits could be achieved if carnallite was also mined. In the summer of 1977, while boring a carnallite trial gallery, an aquifer was punctured and within 36 h the mine was completely flooded. In recent years, feasibility studies have been conducted to determine the possibility of exploiting the resource by conventional mining methods, after pumping out the water, or by solution mining. In any event, it appears as though a few years will pass before production from the remaining resources at Holle (St. Paul) will be realized.

ISRAEL AND JORDAN

The Dead Sea is situated in the lowest part of the Jordan Valley, formed by two massive parallel sets of faults, which is a part of the East African rift. The part of the rift that contains the Dead Sea represents a fault graben that stretches 1,100 km from southern Turkey in the north to the Gulf of Aquaba in the south and ranges from 5 to 20 km in width. The graben was formed during Oligocene times and experienced ingressions of the Mediterranean Sea. At present, about two-thirds of the dissolved salts in the Dead Sea are the result of residual brines of the Pleistocene evaporation cycle and about one-third are from the Jordan River, underground springs, and wadis (streams).

Both Israel and Jordan share in exploiting the Dead Sea resource. The area south of the Lisan Peninsula now contains solar evaporation pans for Israel's Dead Sea Works operations and Jordan's Arab Potash Mine. Dikes of the two sets of evaporation pans are separated by a distance of 500 m. Effluent streams from the two plants flow down a channel between the dikes along the truce line between Israel and Jordan, and then drain into the Dead Sea.

The Dead Sea now has a specific gravity of 1.2 kg/L and is almost completely saturated with sodium chloride. Estimated quantities of salts in solution are shown in table A-3.

Table A-3.—Estimated quantities of dissolved solids in the Dead Sea (*23*), billion metric tons

Potassium chloride (KCl)	2.0
Sodium chloride (NaCl)	12.0
Magnesium chloride ($MgCl_2$)	22.0
Calcium chloride ($CaCl_2$)	6.0
Magnesium bromide ($MgBr_2$)	1.0
Calcium sulfate ($CaSO_4$)	.1

ITALY

In Sicily, the upper Miocene evaporitic Solfifera Series of the central Sicilian Basin or Caltanissetta Trough, which appears in all of the Mediterranean basin, is made up of limestone, salt, and clay. It overlies the upper Tortorian Formation and underlies calcareous marls of lower Pliocene age. The similarity of strata throughout the island provides reason to believe that the whole evaporative sequence formed in a continuous sedimentation basin and that it was later fragmented by tectonic events. The salt formations have been classified into four sedimentary cycles of deposition.

The first cycle is made up of rock salt (NaCl) with interbedded layers of anhydrite and polyhalite. The entire cycle has a thickness of about 100 m. The upper 50 m of this cycle consists of a layer of salt that is about 99 pct NaCl.

The second evaporative cycle is most important in terms of potash resource. The cycle, which is about 200 m thick, is composed of rock salt with layers of anhydrite, polyhalite, and kainite beds. Kainite is the mineral recovered for its K_2O value.

The third evaporative cycle is about 100 m thick and consists of rock salt with layers of anhydrite. Although it is mined at Realmonte, Racalmoto, and Cattolica Eraclea, it has a very low assay value and is not considered important.

The fourth and most recent evaporative cycle is of least importance. The 50-m-thick bed consists of rock salt with intercalated layers of anhydrite with a low average grade (about 90 pct NaCl) making it undesirable for mining potash.

The entire Sicilian salt mineralization forms a belt that extends 550 km northeast-southwest from Nicosia to Sciacca and widens along the southern Sicilian coast from Sciacca to Porto Empedocle.

SPAIN

The three major evaporate sequences of the Iberian Peninsula occurred in the Triassic and Tertiary periods with the Tertiary being of the greatest economic importance. These Spanish deposits are only 45 million yr old and therefore quite recent when compared with those of Canada or the Federal Republic of Germany. The two Spanish potash regions are at the opposite ends of a single large depression that corresponds to the present-day Ebro Valley. Evaporite exists throughout the region and at its extremes are the Catalonia and Navarra potash occurrences. Suria, Cardona, and Llobregat are in the Catalonia side and Esparaza is in the Navarra side.

The sedimentary stratigraphy is similar at either end. From the bottom layers to the top, it is described as limestones and anhydrite, salt, sylvinite seams, alternating layers of carnallite, and younger salt, marls, and a roof of sandstone. The sylvinite is 2 to 5 m thick with occasional maximum thicknesses of up to 8 m, but the most common is 2 m. Carnallite is typically 1 to 4 m thick, averaging 2.5 m. The potash occurrences are commonly encountered at depths of about 500 m but vary in depth from site to site.

The potash seams at Esparza and Llobregat have remained relatively undisturbed geologically, and dip at an angle of approximately 5° to the northeast. There are two sylvinite beds that are separated by a 2-m-thick bed of rock salt.

At Cardona, the potash seam has been subjected to severe folding resulting in a bubblelike shape with dips of 70° to near vertical; the tabular ore body is contained within a hill that is 3.5 km long by 1.5 km wide by over 1,600 m high.

The deposit at Suria has been subjected to postdepositional folding and lack the areal uniformity characteristic of deposits such as those in Saskatchewan, Canada. There are four potash seams in this area. Only the deepest, seams A and B, are currently being mined.

FRANCE

France is currently exploiting potash resources from the Rhine graben of the upper Rhine River Valley. The Rhine graben is a narrow depositional valley that stretches north-south along the French side of the French-German border.

During the Eocene, the Rhine rift started to subside, taking the Rhine graben with it. The valley was then flooded with water from the Mediterranean Sea and a lagoonal environment was set. This environment provided a setting for the first saline precipitation, which included an 800-m series of halite, anhydrite beds with calcareous and dolomitic marls. During the early Oligocene, a second saline precipitation period occurred. This series allowed the formation of the potash beds that are mined today.

Subsidence of the Rhine rift continued into the Pliocene when late alpine folding formed north-south trending flexures, which separate the potash resources. These deposits were discovered in 1904 and have been exploited since 1910.

THE FEDERAL REPUBLIC OF GERMANY

During the Permian period, a large depositional basin, known today as the Zechstein Basin, existed in northwestern Europe. The basin stretched from northern Britain across the North Sea to the Netherlands through Germany and into Poland. The Zechstein was a shallow-shelf sea. The deepest part was around the Elbe River in Germany and extended into the North Sea.

The Zechstein Basin, which makes up most of the rocks of the Permian Age in Northern Europe, is divided into four evaporite cycles. Each cycle follows the same basic pattern and is described as having fine clastic sediments (rotliegendes) known for their red color, carbonate rock, anhydrite, halite, sylvite, anhydrite, and carbonate layers. The carbonate layers are the best developed and therefore are used to define the boundaries of the Zechstein Basin throughout northwestern Europe including the United Kingdom, Federal Republic of Germany, German Democratic Republic, the Netherlands, and Poland. Although all the potash in northwest Europe is in the Zechstein Basin, each area that is currently being mined has small differences which will be discussed separately.

In the Federal Republic of Germany, potassium and magnesium salts were deposited during supersaline stages of evaporite cycles. Four cycles containing five potash members have been identified in this region. In the southern Werra-Fulda district, deposition was short lived when compared with deposition in the northern lower-Saxony district. In the south only the Werra Series was deposited, whereas in the north the entire succession is present.

The great thickness of low-density evaporites in the lower Saxony district has caused extensive folding. Consequently, the potash deposits are usually steeply dipping and thickness varies greatly over short distances. Mining has occurred at depths ranging between 200 and 1,000 m.

In the Werra-Fulda district, ore thickness and depth to ore are relatively uniform, 2.5 to 3.5 m and approximately 500 m, respectively. The Hessen seam is mined at each of the three operating southern mines (Wintershall, Neuoff-Elers, and Hattorf), for both potash and kieserite.

Potash has been mined from the Zechstein Basin since the late 19th century. The Zechstein Basin became a major potash supplier in the early 20th century. Today, although still important, resources from Zechstein Basin have taken a secondary position to the more plentiful resources of Canada and other major producers.

UNITED KINGDOM

Three evaporite deposits are present in the Cleveland and North Yorkshire regions. At the Boulby Mine, potash beds are intersected at a depth of about 1,100 m. A rock salt layer contacts the base of the potash zone. This contact is relatively planar. However, the upper transition zone

contact is substantially more irregular and material above the transition zone is very weak. The carnallite marl consists primarily of halite and dehydrated clay minerals with negligible cementation and low structural strength. These factors contribute to roof stability problems.

THAILAND

Potash was first discovered in Thailand in 1973 when the Thailand Department of Mineral Resources, while exploring for water, drilled into a thick section of almost pure carnallite. An extensive drilling program, which followed, defined the Khorat Plateau as having potential potash resources equal to or greater than those of Saskatchewan, Canada. There are no demonstrated resources of sylvite, and carnallite is not currently considered potash ore.

The plateau consists of three evaporite zones. From north to south, they are the Sakon Nakhon Basin, the Phu-Phan anticlinorium, and the Khorat Basin. Each zone has three evaporite units named Upper Salt, Middle Salt, and Lower Salt. So far exploration has found potash only in the Lower Salt unit.

Potash resources in the Khorat Plateau are mostly in the form of carnallite. Sylvinite deposits are usually small lenses and are not workable. Larger sylvinite deposits such as those near the cities of Khon Kaen, Udon Thani, and Wanon Niwat have not been explored in great enough detail to determine if they can be economically mined. There is a lack of detailed information on resource tonnages; however, there are indications that this area could prove to be a major future producer of potash.

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